Experimental Study of a Novel Digital Optical Switch

By

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Abstract

The basic structure, electrical and optical characteristics of a novel digital optical switch (DOS) fabricated in InGaAsP are studied. The semiconductor layers of the DOS form a p-i-n diode. The switching is achieved by free carrier injection from metal electrodes into a ridge waveguide.

Contact resistivity measurements for Ti/Pt/Au electrodes on doped InGaAsP are reported using the transmission line method. These experiments are performed before and after Oxygen ion implantation of the semiconductor to determine the degree of electrical isolation between contact electrodes. Contact resistivity is improved by 10^4 times after ion implantation.

A straight section of ridge waveguide with and without metal electrode was studied experimentally. The waveguide with cleaved ends formed a Fabry-Perot cavity. A broadband optical source was used to obtain waveguide loss and refractive index change due to carrier injection under forward bias in the p-i-n diode structure. Different waveguide widths (3 μm , 4 μm , 5 μm) were studied. The 3 μm waveguide had loss of about 5 dB/cm for the TE mode and 16 dB/cm for the TM mode. A refractive index change of 0.3×10^{-3} could be achieved with forward current density of 2000 A/cm².

The switching characteristics of a Y-branch DOS switch were measured. The switch electrodes had an RC time constant of about 17.9 ps with $R \sim 5.25 \Omega$. After correction for measurement system rise-time, the DOS switch time was determined to be ~ 7 ns.

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List of Symbols & Abbreviations

DOS	Digital Optical Switch
TLM	Transmission Line Model
TIR	Total Internal Reflection
TE	Transverse Electric polarization mode
TM	Transverse Magnetic polarization mode
n	Refractive index
λ	Wavelength
Δn	Change in refractive index
$\Delta \lambda$	Spectral wavelength width
N	Number of switches per dimension
C	Capacitance
R	Resistance
ρ_c	Specific contact resistance. Also called contact resistivity
R_c	Contact resistance
R_s	Sheet resistance
R_t	Total resistance between the two pads
s	Contact spacing
L_t	Transfer length.
w	Pad width
d	Pad length
R_{sk}	Sheet resistance under the contact
ρ_{ck}	Specific contact resistance calculated from the Reeves and Harrison model
R_e	End resistance.
L_{tk}	Transfer length calculated from the Reeves and Harrison model
ϵ_o	Permittivity of free space
ϵ_r	Dielectric constant
C_j	Junction capacitance
C_p	Parasitic capacitance
I	Current passing through the waveguide
V	Potential applied to the waveguide electrode.
$\tau_{RC} = RC$	Rise time constant
τ_{gen}	Pulse generator rise time
τ_{osc}	Oscilloscope response time
τ_{probe}	Probe rise time
τ_{meas}	Measured rise time
τ_{switch}	Switch rise time

1 Introduction

1.1 An Overview of Optical Switches

Optical switches play a key role in optical communication networks. They can perform optically transparent network reconfiguration, routing, optical cross connect and optical packet switching [1 – 6]. The switch arrays, in combination with passive wavelength multiplexers and demultiplexers, can be used to realize dynamic reconfigurable wavelength routers and wavelength add /drop multiplexers. Nowadays, the dense wavelength division multiplexing (DWDM) technology is broadening its applications from long haul point-to-point transmission systems to metropolitan and local area access networks. As a result, compact, low cost and high-performance optical switches and arrays are required.

A number of waveguide based optical switches have been developed. They include interferometric devices such as directional couplers and Mach-Zehnder interferometers, digital optical switches based on modal evolution in conventional Y-junctions, total internal reflection (TIR), and field-induced waveguide formation.

Directional couplers and Mach-Zehnder interferometers are both based on mode interference effects [7]. They require a precise drive-voltage or current control in order to achieve the switching with a high extinction ratio. The operating voltage or current is dependent on wavelength, thus making multi-wavelength simultaneous switching impossible in WDM systems. They are also sensitive to polarization and temperature and have small fabrication tolerances.

A digital optical switch (DOS) is a 1 X 2 or 2 X 2 optical switch. Digital optical switches exhibit a digital transfer response for a large ratio for ON/OFF voltage or current [6]. The switch design will determine the sensitivity of the switch to wavelength, polarization and temperature [1]. The most commonly used form of DOS is the linear Y-junction branch as illustrated in Fig. 1.1. Its operating principle is based on adiabatic mode evolution rather than mode interference as in the case of directional coupler and Mach-Zehnder interferometers. In order to ensure adiabatic mode coupling, the angle between the branching waveguides needs to be very small. This leads to a long device length [8, 9]. Since a switch array with a large number of input/output ports requires cascading of many stages of switches, a small device length is highly desirable. The adiabatic coupling also requires that the waveguide structure be weakly guiding so that its index step can be modified by a small index change induced by the drive current/voltage. The cladding layer thickness and etching depth thus needs to be accurately controlled and fabrication-induced strain must be minimized to avoid stress-induced guiding or anti-guiding effects. Another practical issue is the crosstalk. Although several structures have been proposed to improve the crosstalk, no experiment has been reported with crosstalk lower than -20 dB and the theoretically calculated crosstalk is in the order of -25 dB for a single stage switch [10].

Another form of DOS, based on guided mode total internal reflection (TIR)[11], is illustrated in Fig. 1. 2. Two single mode waveguides intersect at a small angle. A metal contact covering half of the intersection region is deposited on the top surface of the waveguide. When current is injected into the active region, the refractive index decreases and a total internal reflection interface is formed which switches the light from one output

Fig. 1.1 Ridge waveguide geometry of the Y-junction digital optical switch for (a) Top view and (b) Cross section at AA'. The cross section at BB' is the same as that of AA' with one ridge and no ohmic contact

Fig. 1. 2 The 2x2 guided mode TIR silicon switch.

port to another. The intersection angle is relatively large and, therefore, a compact switch can be fabricated. The switch also exhibits digital response and is insensitive to wavelength and polarization. However, a large refractive index change is required in order to achieve the total internal reflection condition. Furthermore, switching characteristics of the reflection and transmission ports are asymmetrical, which may limit its use for certain applications.

Another type of switch, based on field-induced waveguides consists of an X- or Y-junction [11]. The lateral optical confinement in the input branches is achieved by using ridge waveguides. In the output branches, only metal contacts are formed and no lateral confinement exists initially. When one of the outputs is reverse biased, the refractive index of the region underneath the metal contact increases (through the quantum confined stark effect or the carrier depletion effect) and thus the lateral confinement is achieved. The optical signal at the corresponding output port increases due to the waveguiding effect. A major problem with this device is the high loss, since no or little optical power is transferred from the OFF port to the ON port during the switching except for a small coupling effecting junction region [11].

At the moment, there are many devices available for low speed optical switching. Thermo-optic polymer switches [12 - 14], micro-electromechanical switches (MEMS) [15 – 18] and liquid crystal switches [14, 19] have switching times in the range of milliseconds (ms). These are sufficient for near/mid term applications such as network cross-connect and protection applications.

However, for switching times in the range of nanoseconds (ns) or picoseconds (ps) regimes, the options are few. Mach-Zehnder switches as in Lithium Niobate

(LiNbO₃) [20 – 22] can switch in the nanoseconds regime but, to achieve this speed at low voltage, long devices are required. As a result the device is not scalable to larger switching fabrics. Polarization dependence represents another problem with LiNbO₃ waveguide devices.

For these reasons, attention has been focused on fast refractive index change effects in III-V semiconductor materials, such as Gallium Arsenide (GaAs) and Indium Phosphide (InP). The basic idea of using the III-V or other semiconductor materials in a switch structure is to cause a refractive index change, Δn , to divert the light to the desired output. Carrier injection or electro-optic effects are able to change the refractive index [7, 23]. Carrier injection produces a change in refractive index of about two orders of magnitude larger than the change induced by electro-optic effects [24, 25]. Moreover, it is not dependent on polarization, unlike the case of electro-optic effects. Thus polarization and wavelength independent switches are thought to be feasible using carrier injection in InP material. Their implementation in InGaAsP/InP material system also allows monolithic integration with semiconductor optical amplifiers that can compensate for the overall loss of the switches.

1.2 A Novel DOS for Study

A novel design for a low-loss DOS based on carrier injection or depletion in InGaAsP/InP has been patented by the National Research Council (NRC) personnel (J. J. He et al.) [11]. The structure of the 1 X 2 switch is shown in Figs. 1. 3 and 1. 4. It consists of two intersecting curved output waveguides, which connect smoothly with an input waveguide. A shaped metal electrode is positioned on top of each

of the output waveguides at the Y-branch. The electrodes are separated by a narrow gap and extend in a smooth continuation of the inner edge of the other waveguide so as to provide a smooth transition from the input waveguide to an output waveguide.

Depending on the bias applied, the switch can broadcast the input light to both outputs, switch the light to one of the outputs, or block the light from both outputs. Such a switch is a versatile building block in a larger $N \times N$ switch or router.

The patent description of the switch is as follows . It consists of an input waveguide, 1, and output waveguides, 2 and 3, formed on a waveguide slab, 4, and dividing from the input waveguide at the junction, 5. The division of the waveguides occurs in the form of smooth curves, of known curvature, in order to obtain a smooth connection with the input waveguide. A metal contact pattern is deposited on top of each output waveguide. The pattern comprises one electrode, 6, on waveguide 2 and one electrode, 7, on the other, 3. The electrodes have larger width than the waveguide as shown in Fig 1. 4. This is not shown in Fig.1. 3 for simplicity. A smooth continuation of the inner edge, 8, of the waveguide 3 extends in a smooth curved-fashion at the junction 5 forming an inner edge, 9, at the electrode 6. A gap, 10, separates the inner edge 9 from the edge of electrode 6. Similarly, a smooth continuation of the inner edge, 11, of the waveguide 2 extends in a smooth curved-fashion at the junction 5 forming an inner edge, 12, at the electrode 7. A gap 13 separates the inner edge 12 from the electrode 7.

With an input signal on the input waveguide 1 and no potential applied to the electrodes 6 and 7, no change will occur in the refractive index of the actual waveguide and the signal will be directed equally between the two output waveguides 2 and 3. If a potential is applied across electrode 6 and also across electrode 7 the refractive index of

Fig. 1.3 Top view of the Y-junction digital optical switch

1: input waveguide, 2 and 3: output waveguides, 4: waveguide slab, 5: junction between the input and output waveguides, 6 and 7: the ohmic contact on top of the output waveguides, 8 and 11: inner edges of the output waveguides, 9 and 12: inner edges of the output waveguides at the junction (5), 10 and 13: gaps separating the inner edges (9 and 12) from the electrodes edges [11].

Fig. 1.4 Cross section of the Y-junction digital optical switch at (a) line AA', (b) BB and (c) CC'

the waveguide under the electrode will decrease due to the carrier injection and as a result, the signal will not propagate along either of the output waveguides. Similarly, if potential is applied only to one of the two electrodes, say 6, then the signal will be blocked from the waveguide having this electrode, 2, Thus, the signal will propagate along the other waveguide, 3, In other words, if a potential applied to an electrode, the signal will propagate along the waveguide of the other electrode.

The switch studied in this thesis uses InGaAsP/InP semiconductor. The devices were made at the National Research Council, Institute of Microstructure Sciences (NRC-IMS) using chemical beam epitaxy (CBE) and reactive ion etching (RIE). The applied potential is a forward bias sufficient to induce the desired change in the waveguide refractive index. Carriers are injected resulting in a decrease in the refractive index in the region beneath the metal contact. Index step will guide the light into the ON branch. With the curved profiles of the electrodes 6 and 7, smooth waveguides are formed from the input waveguide 1 to the output waveguides 2 and 3. This reduces the losses in the switching to low levels.

Although the symmetric Y-junction waveguide branches look similar to the conventional DOS using adiabatic mode evolution, the switching mechanism is different. The principle of operation of this 1x2 switch is closer to the TIR switch [26] if the waveguide wall formed by the carrier injection is viewed as a total internal reflection mirror. The switch is therefore very compact. The required electrode length is much shorter than the DOS using adiabatic mode evolution. Due to the curved waveguiding geometry, the required index step change is much smaller than in case of conventional TIR switches. In addition to the formation of the waveguide wall for the ON port, the

waveguide at the OFF port is deformed at the same time. This further reduces the crosstalk. Carrier induced absorption in the OFF branch, in the region below the forward biased electrode, further improves the extinction ratio of the device.

1.3 Electrical and Optical Design Issues in the Proposed DOS

The switch must be designed carefully to both confine and isolate the carrier injection effects of each electrode, as well as to provide low loss single mode spatial waveguiding. The Y-switch needs electrical isolation of the 2 contacts so that current will not pass from the OFF branch to the ON branch (grounded) under the influence of potential difference. If there is no such electrical isolation, then the carriers will pass to the other branch and the contrast, or extinction ratio, between the two branches will be small. Moreover, the loss in the switch will be very high. By creating a high resistance region between the two branches, this isolation can be achieved. This isolation does not only reduce the lateral leakage currents, but also reduces the parasitic capacitance and waveguide loss. Under appropriate conditions, ion bombardment of the III-V semiconductors can increase the resistivity significantly via creation of deep level centers, which effectively remove free carriers from the conduction process [27 - 29]. Also, choosing layers of higher band gap to surround the active region can achieve confinement of the carriers beneath the ridge. In this case, the leakage of carriers away from the junction will be reduced.

If the optic axis is the z-axis, there will be optical confinement in both x- and y- directions. Optical confinement is achieved as shown in Fig. 1. 4. The x- direction confinement is due to the presence of the ridge. The effective refractive index in the

region beneath the ridge is larger than the effective index in the adjacent regions [23].

In the y-direction, the confinement is achieved due to the presence of the core, the active region, of higher refractive index between two layers of lower refractive index. If one or both of the two confinements were not achieved, light guiding would not be achieved.

1.4 Focus of Study

This thesis is focused on the experimental investigation of two distinctly different technology issues for successful design of the proposed DOS. First, the ohmic contact of the metal electrodes to the InGaAsP/InP semiconductor layers and the electrical isolation between electrodes before and after implantation of oxygen ions into the region between the electrodes are characterized. Second, guided modes, optical loss and polarization sensitivity of the optical waveguides with and without the presence of the metal electrodes and with and without the forward bias applied are characterized. Loss measurements are obtained using the Fabry-Perot cavity technique [30, 31].

1.5 Thesis Outline

This thesis has five chapters. This chapter has dealt with the technologies and basic structures available for optical switching. A novel DOS structure using carrier injection in InGaAsP/InP has been discussed.

Basic electrical and optical parameters of this switch structure will be presented in the next four chapters. Chapter 2 deals with the contact resistance and sheet resistance measurements, before and after implantation with Oxygen ions. Chapter 3 discusses the electrical characterization of the active waveguide formed by the electrodes and PIN

diode layers in the InGaAsP/InP. Chapter 4 discusses the optical characterization of this waveguide, primarily by Fabry-Perot cavity measurements. In Chapter 5, the switching curves and switching simulation, in addition to the simulation of the contribution of first-order light mode in the waveguide output power, are discussed. Conclusions and recommendations for further study are presented in Chapter 6.

2 Characterization of the DOS Electrodes

2.1 Introduction

One of the most common methods for quantitatively assessing the performance of ohmic contacts to semiconductors is to measure the value of specific contact resistance ρ_c , also called contact resistivity, whose unit is $\Omega\text{-cm}^2$. Multiplying the contact resistance, R_c , by the contact area, determines this two-dimensional resistivity.

Sheet resistance R_s , the resistivity per unit thickness ($\Omega/\square$), is often needed as a design parameter in the analysis of semiconductor layers and metal layers.

A useful tool for analyzing planar contacts is the transmission line model (TLM), originally proposed by Shockley [32] and developed by Murrmann and Widmann [33]

In an ohmic contact system, ρ_c can be determined using test patterns of circular or rectangular geometry. Only rectangular geometry will be discussed in this work. Fig. 2. 1 shows the rectangular geometry of TLMs. The four-point sheet resistance measurement technique is used with this rectangular electrode pattern. In this technique, as shown in Fig. 2. 2, a current is forced through the adjacent pairs of rectangular contact pads. The voltage drop across the same pads is measured as a function of current. For an ohmic contact system the relation is linear and the total resistance between the two pads, R_t , is the slope of the line. A typical plot of the total resistance between contacts as a function of the contact spacing is shown in Fig. 2. 3. It was seen that the total resistance increases linearly with the contact spacings. These measurements are done before and after

Fig. 2. 1 Rectangular geometry of the electrode pattern for TLM measurements

Fig. 2. 2 Determination of the total resistance between the square pads using the four-probe technique

Fig. 2. 3 A typical plot of the total resistance, R_t , measured between contacts for different electrode spacing, s . R_c is the contact resistance and L_t is called the transfer length.

implantation (and annealing) to determine the electrical isolation between electrodes.

2.2 Sample Description and Total Resistance Measurement

National Research Council (NRC) personnel designed two DOS samples with different composition for carrier injection operation. Both samples were grown by chemical beam epitaxy (CBE) and reactive ion etching (RIE) on (001) oriented InP substrates. Tables 2. 1 and 2. 2 show the composition, thickness and doping level for the two samples. A metal stack of titanium, platinum and gold (TiPtAu) was deposited and patterned to form the metal electrode pads. The two samples were quarter wafers cleaved into five sections labeled A to E. Each section had test patterns as shown in Fig. 1. 1 with contacts of dimensions $w \times d$ and varying spacing s . The tested geometries are listed in Table 2. 3. Sample 1 had 2000 Å of metalization and sample 2 had 4000 Å of metalization. The Ti/Pt/Au composition is also listed in Table 2 .3. This metalization mask acts as a barrier for the oxygen ion implantation process. The samples were then implanted with different doses and energies of oxygen ions according to the schedule in Table 2. 4. All implants were done at 22.5°C with beam current density $25 \pm 5 \text{ nA/cm}^2$. For sample 1, each implanted section was divided into two parts. One part was annealed at 350°C for 5 minutes and the other part was annealed at 450°C for 5 minutes. For Sample 2, all sections were annealed at 22.5°C.

2.3 Contact Resistance and Sheet Resistance using Marlow and Das Model

Marlow and Das [34] showed that the relation between total resistance, R_t , and

Table 2. 1: The structure of sample 1

Layer	Layer Composition	Thickness (μm)	Concentration of Dopant (cm^{-3})	Dopant Type
Electrode Metal	TiPtAu	0.2		
Cap	$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	0.1	1×10^{19}	p (Be)
Cladding	InP	0.3	5×10^{17}	p (Be)
Etch Stop	InGaAsP (1.3 μm)	0.01	undoped	
Cladding	InP	0.2	undoped	
Core	InGaAsP(1.3 μm)	0.5	undoped	
Buffer	InP	0.3	undoped	
Buffer	InP	0.7	1×10^{18}	n(Si)
Substrate	InP	~140	$4-8 \times 10^{18}$	n(S)

Table 2. 2: The structure of sample 2

Layer	Layer Composition	Thickness (μm)	Concentration of Dopant (cm^{-3})	Dopant Type
Electrode Metal	TiPtAu	0.4		
Cap	$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	0.1	1×10^{19}	p(Zn/Be)
Cladding	InP	0.3	5×10^{17}	p(Zn/Be)
Cladding	InP	0.5	undoped	
Etch Stop	InGaAsP(1.3 μm)	0.01	undoped	
Cladding	InP	0.2	undoped	
Core	InGaAsP(1.3 μm)	0.5	undoped	
Buffer	InP	0.3	undoped	
Buffer	InP	0.7	1×10^{18}	n(Si)
Substrate	InP	~140	5×10^{18}	n(S)

Table 2. 3: Geometry of the TLM test patterns

Sample	w (μm)	d (μm)	s (μm)	Number of TLM Patterns		Top Contact Thickness ($\text{\AA}$) (Ti/Pt/Au)
				TLM Status	#	
1	100	100	3, 7, 11.5, 14.5, 23 and 31	Non-Implanted	25	2000 (350/350/1300)
				Implanted + 350°C	6	
				Implanted + 450°C	7	
2	50	50	1, 2, 5, 10, 15 and 25	Non-Implanted	9	4000 (750/750/2500)
				Implanted	3	
2	50	25	1, 2, 5, 10, 15 and 25	Non-Implanted	2	4000 (750/750/2500)
				Implanted	3	

Table 2. 4: Test matrix for oxygen implantation

Sample	Section	Oxygen Ions Implantation			Annealing Temperature (°C)	tested
		Ion Energy (keV)	Surface concentration (Ions / cm^2)	Time (minutes)		
1	A	60 +140	$2 \times 10^{14} + 5 \times 10^{14}$	26 + 72	350 and 450	Yes
	B	60 +140	$4 \times 10^{13} + 1 \times 10^{14}$	5 + 15	350 and 450	Yes
	C	60 +140	$4 \times 10^{14} + 1 \times 10^{15}$	56 + 79	350 and 450	Yes
2	A	150	1×10^{14}	30	22.5	Yes
	B	150	2×10^{14}	30	22.5	Yes
	E	150	1×10^{14}	30	22.5	No

electrode spacing, s , is a straight line with slope proportional to sheet resistance, R_s . The line intercepts the positive R_t axis at $2R_c$, where R_c is the contact resistance. The line intercepts the negative s axis at $-2L_t$, where L_t is called the transfer length. This relation is shown in Fig. 2. 3. Fig 2. 4 shows the Marlow and Das model transmission line model (TLM) for square contact pads separated by spacing s . They showed that for $w \gg L_t$, R_t can be expressed in terms of R_s , s , w and R_c as follows:

$$R_t = 2 R_c + R_s \left(\frac{s}{w} \right) \quad (2.1)$$

where w is the pad width as shown in Fig. 2.1. That is R_t is composed of the resistance of the two contacts, $2R_c$, in series with the resistance of the semiconductor, $R_s(s/w)$, between the two contacts. The contact resistance, R_c , can be written as

$$R_c = R_s \left(\frac{L_t}{w} \right) \quad (2.2)$$

The semiconductor resistance between the contacts is the sheet resistance, in $\Omega/\square$, times the number of squares, s/w , of the resistive region between contacts. In the same manner, the contact resistance is the sheet resistance times the number of squares, L_t/w , under the contact region. Thus the transfer length L_t can be regarded as the equivalent length of the resistive region under the contacts.

Now we can get the contact resistivity (ρ_c) as follows:

$$\rho_c = R_s \cdot L_t^2 \quad (2.3)$$

or

$$\rho_c = R_c \cdot w \cdot L_t \quad (2.4)$$

Fig. 2. 4 Equivalent circuit for the Marlow and Das TLM model [34]

Fig. 2. 5 Equivalent circuit for the Reeves and Harrison TLM model [35]

ρ_c sometimes called the specific contact resistance. Eqn. (2.3) gives the value of ρ_c while Eqn. (2.4) shows the meaning of it as simply the product of the contact resistance and the area in which this contact resistance spreads.

From Eqn. (2.1), linear interpolation of the total resistance, R_t , versus spacing, s , data will have a slope R_s / w and intersect equal to $2 R_c$. The transfer length L_t can be calculated from Eqn. (2.2). Finally, ρ_c can be calculated from Eqns. (2.3) or (2.4). The IV data for one TLM pattern on samples 1 and 2 prior to implantation are shown in Figs. 2. 6 and 2. 7. Figs. 2. 8 and 2. 9 show the total resistance, R_t , as a function of contact pad spacings, s , for all TLM patterns of samples 1 and 2 before implantation. A solid line in Figs. 2.8 and 2. 9 shows the average total resistance.

For sample 1, the variation from the average total resistance ranges from +7 % to -20 % for $s = 3 \mu\text{m}$ and from + 7% to -14 % for $s = 31 \mu\text{m}$. For sample 2, the variation from the average total resistance ranges from +25 % to -30 % for $s = 1 \mu\text{m}$ and from +6 % to -7 % for $s = 25 \mu\text{m}$. Scatter plots for R_s , R_c , L_t and ρ_c are shown in Figs. 2.10 and 2.11. A solid line in Figs. 2. 10 and 2. 11 show the average value for R_s , R_c , L_t and ρ_c .

The Marlow and Das model is simple and convenient. It can be used to determine the approximate value of contact resistivity. Marlow and Das assumed that the sheet resistance for the semiconductor region between the contacts is the same as that under the contacts. However, the sheet resistance under the contact, R_{sk} , is different than R_s . For a more accurate value of the contact resistivity, an improved model, which takes this difference into account, should be used. Reeves and Harrison model [35] was used to

Fig. 2. 6 Voltage drop between the contacts of sample 1 before implantation versus the current passing through the spacing between the contacts, s , at different values of “ s ”.

Fig. 2. 7 Voltage drop between the contacts of sample 2 before implantation versus the current passing through the spacing between the contacts, s , at different values of “ s ”.

Fig. 2. 8 Total resistance, R_t , measured between contacts on sample 1 for different electrode spacing, s , before implantation. Measurements are made for 25 TLMs. The solid line shows the average total resistance. The minimum and maximum values of R_t for each spacing s are also indicated.

Fig. 2. 9 Total resistance, R_t , measured between contacts on sample 2 for different electrode spacing, s , before implantation. Measurements are made for 12 TLMs. The solid line shows the average total resistance. The minimum and maximum values of R_t for each spacing s are also indicated.

(a)

(b)

(c)

(d)

Fig. 2. 10 Scatter plot of measured values of (a) R_s , (b) R_c , (c) L_t and (d) ρ_c before implantation for different TLMs of sample 1. The Marlow and Das model [34] was used in the calculation. The solid line shows the average value. The minimum and maximum values are also indicated.

(a)

(b)

(c)

(d)

Fig. 2. 11 Scatter plot of measured values of (a) R_s , (b) R_c , (c) L_t and (d) ρ_c before implantation for different TLMs of sample 2. The Marlow and Das model [34] was used in the calculation. The solid line shows the average value. The minimum and maximum values are also indicated.

determine accurate contact resistivity as shown in the next section.

2.4 Contact Resistance and Sheet Resistance using the Reeves and Harrison Model

Reeves and Harrison [35] proposed a more accurate model than that of Marlow and Das[34]. In this model, Reeves and Harrison proposed that the sheet resistance of the semiconductor outside the contact region R_s does not equal the sheet resistance of the layer directly under the contact R_{sk} . Eqn. (2.1) is still valid, but Eqn. (2.2) becomes:

$$R_c = \frac{R_{sk} \cdot L_{tk}}{w} \coth\left(\frac{d}{L_{tk}}\right) \quad (2.5)$$

and ρ_c becomes ρ_{ck}

$$\rho_{ck} = R_{sk} \cdot L_{tk}^2 \quad (2.6)$$

For $d \gg 2L_{tk}$, Eqn. (2.5) can be written as follows:

$$R_c \cong \frac{R_{sk} \cdot L_{tk}}{w} \quad (2.7)$$

The letter “k” is added as a subscript to indicate that these quantities are calculated using Reeves and Harrison model [35]. Their model is also based on a set of three contacts as shown in Fig. 2. 5. Resistances R_1 , R_2 and R_3 are the total resistances measured between contacts 1 and 2, 2 and 3, and 1 and 3 respectively. The resistance under the middle contact 2 is modeled as a T-network of two series resistors of value $R_c - R_e$ and one parallel resistor of value R_e , where R_e is called the end resistance. R_e is calculated from

$$R_e = \frac{(R_1 + R_2 - R_3)}{2} \quad (2.8)$$

From the relation

$$\frac{R_c}{R_e} = \cosh\left(\frac{d}{L_{tk}}\right) \quad (2.9)$$

We obtain the transfer length for the Reeves and Harrison model, L_{tk}

$$L_{tk} = \frac{d}{\cosh^{-1}\left(\frac{R_c}{R_e}\right)} \quad (2.10)$$

R_s , R_{sk} , L_t , L_{tk} , R_c , R_e , ρ_c and ρ_{ck} were calculated using the above equations.

Unfortunately, sections A, B and C of sample 1 were exposed to implantation and annealing. Section D was exposed to implantation without annealing but all the TLMs were damaged. Section E was not exposed to implantation or annealing. The last five points in Fig. 2. 10 represent the TLMs of section E. Therefore, we measured R_3 , as shown in Fig 2.5, according to Reeves and Harrison model [35], only for section E.

Figs. 2. 12 and 2. 13 show the values of R_{sk} , R_e , L_{tk} and ρ_{ck} using the Reeves and Harrison model [35] for samples 1 and 2 before implantation and annealing. Note that for every TLM, the values for R_s and R_c from the Reeves and Harrison model are the same as those from the Marlow and Das model. R_s and R_c are shown in Figs. 2.10 (a) and 2.10 (b) for sample 1 and in Figs. 2.11(a) and 2.11 (b) for sample 2, respectively.

2.5 Discussion of Results from Samples 1 and 2 before Implantation

Figs. 2. 10 and 2. 11 show scatter plots of measured values of R_s , R_c , L_t and ρ_c using the Marlow and Das model [34] for samples 1 and 2 before implantation.

Figs. 2. 12 and 2. 13 show scatter plots of measured values of R_{sk} , R_e , L_{tk} and ρ_{ck}

(a)

(b)

(c)

(d)

Fig. 2.12 Scatter plot of measured values of (a) R_{sk} , (b) R_e , (c) L_{tk} and (d) ρ_{ck} before implantation for different TLMs of sample 1. The Reeves and Harrison model [35] was used in the calculation. The solid line shows the average value. The minimum and maximum values are also indicated.

(a)

(b)

(c)

(d)

Fig. 2.13 Scatter plot of measured values of (a) R_{sk} , (b) R_e , (c) L_{tk} and (d) ρ_{ck} before implantation for different TLMs of sample 2. The Reeves and Harrison model [35] was used in the calculation. The solid line shows the average value. The minimum and maximum values are also indicated.

using the Reeves and Harrison model [35] for samples 1 and 2 before implantation.

For Each TLM, R_s and R_c are the same for both models. The maximum, minimum and average values for the above quantities are shown in the figures of the scatter plots mentioned above.

Tables 2. 5 and 2. 6 summarize the results obtained from Figs. 2. 10 – 2. 13.

From Tables 2. 5 and 2. 6, it is clear that L_t and ρ_c values, according to the Marlow and Das model [34], are far larger than L_{tk} and ρ_{ck} , for the Reeves and Harrison model [35].

In other words, L_t and ρ_c are over estimated due to the over estimation of the sheet resistance under the contact pads ($R_{sk} = R_s$). The Reeves and Harrison model [35] is more accurate and reliable than the Marlow and Das model [34], but the Marlow and Das model is easier and more convenient for comparing different structures where accuracy is not the most important factor.

By comparing the values of R_s , R_{sk} , R_c , R_e , L_t , L_{tk} , ρ_c and ρ_{ck} of sample 1 with those of sample 2 it was found that sample 2 has lower values of all parameters except for R_{sk} . The thicker (0.4 μm) metalization on sample 2 leads to lower contact resistance and should be used as the metalization for the contact electrodes on the experimental switch.

The differences in the values of R_s , R_c , L_t and ρ_c for different samples may be attributed to:

- imprecise measurements of dimensions s , w and d
- invisible defects introduced during fabrication
- exposure of the samples to many processes and handling by many people
- inconsistent probe placement and spacing

Table 2. 5: Maximum, minimum and average values of R_s , R_c , L_t and ρ_c for different TLMs of samples 1 and 2 before implantation. The Marlow and Das model was used in the calculations of R_s , R_c , L_t and ρ_c .

		R_s ($\Omega / \square$)	R_c (Ω)	L_t (μm)	ρ_c $\times 10^{-5}$ ($\Omega - cm^2$)
Maximum	Sample 1	1087.5	28.4	2.74	6.7
	Sample 2	577.26	21.54	2	2.15
Minimum	Sample 1	821.27	14.29	1.47	2.14
	Sample 2	508.98	8.43	0.82	0.35
Average	Sample 1	913.3 ± 80	19.6 ± 3	2.14 0 ± 0.25	4.2 ± 1
	Sample 2	547.7 ± 25	12.8 ± 1.5	1.18 ± 0.15	0.84 ± 0.1

Table 2. 6: Maximum, minimum and average values of R_{sk} , R_e , L_{tk} and ρ_{ck} for different TLMs of samples 1 and 2 before implantation. The Reeves and Harrison model was used in the calculations of R_{sk} , R_e , L_{tk} and ρ_{ck} . R_s and R_c are the same as in Table 2. 5.

		R_{sk} ($\Omega / \square$)	R_e (Ω)	L_{tk} (μm)	ρ_{ck} $\times 10^{-5}$ ($\Omega - cm^2$)
Maximum	Sample 1	81.28	2.28	33.74	76.62
	Sample 2	168.4	2.15	16.42	8.27
Minimum	Sample 1	55.49	1.7	30.02	62.5
	Sample 2	30.16	0.64	6.39	3.37
Average	Sample 1	68.63 ± 9.3	1.92 ± 0.2	32.24 ± 1.66	70.5 ± 4.5
	Sample 2	75.24 ± 33.3	1.00 ± 0.27	9.89 ± 3.06	5.97 ± 3.47

- scratches on some of the metal contact
- differences in probe tip pressure and sample contact
- variations in room temperature and humidity

2.6 Characterization of Samples 1 and 2 after Implantation

After implantation, and annealing in case of sample 1, I-V curves of the six s values for TLMs of sample 1 and 2 were plotted. Typical plots for TLMs of sample 1, after implantation and annealing at temperature 350°C and 450°C, and sample 2, after implantation, are shown in Figs. 2. 14 and 2. 15, respectively. The plots can be divided into three linear sections. The two end parts of the plot are of less resistance, or slope, than in the center. This can be explained based on the structure of the TLM.

The basic structure of the TLM is a P-I-N diode. Each TLM has two P-type layers ($\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and InP) and two n-type layers (both composed of InP material) of different dopant concentration. The layers in between the n- and p-type InP layers are undoped, form an intrinsic layer with total thickness 1.51 μm . The P-I-N structure of the waveguide will be discussed in more details in Chapter 3.

After implantation, this part of p region between the metal electrodes, or contacts, will be implanted with oxygen and, therefore, the resistance of this part is very high and electrical isolation between the contacts takes place. This isolation divides the TLM into two back-to-back P-I-N diodes. Fig.2.14 shows the electrical model of the TLM after implantation and its equivalent circuit.

When the positive voltage is applied, P-I-N diode 1 is forward biased (ON) and P-I-N diode 2 is reverse biased (OFF). Therefore the TLM behavior when positive voltage is

Fig. 2. 14 Electrical model of the TLM after implantation and its equivalent circuit.

applied is due to the behavior of the forward biased P-I-N diode 1.

When the negative voltage is applied, P-I-N diode 2 is forward biased (ON) and P-I-N diode 1 is reverse biased (OFF). Therefore the TLM behavior when negative voltage is applied is due to the behavior of the forward biased P-I-N diode 2.

The IV curves are simply the curves of P-I-N diodes 1 and 2 in the forward bias mode.

The Marlow and Das model [34] and the Reeves and Harrison model [35] are not applicable for the TLMs after implantation because of the back-to-back diode structure. The reverse biased P-I-N diode is responsible for the overestimation of the contact resistance. However, it is useful to proceed into the contact resistivity calculations for the purpose of comparison among the different TLMs.

Figs. 2-15 and 2-16 show the voltage drop as a function of the current for TLMs for samples 1 and 2 after implantation. There are two regimes shown in Figs. 2-15 and 2-16. The first regime is of higher slope (total resistance) and represented as the central region with approximately constant slope. This regime takes place when the applied voltage is less than the turn-on voltage of the forward biased P-I-N diode. As the voltage amplitude exceeds the turn-on voltage, charge carriers gain enough energy to cross the junction between the p and n regions. This regime is represented in Figs. 2-15 and 2-16 as the two extremes of the curve with approximately constant resistance less than the resistance of the central region.

For sample 1, after calculating the resistance for the three regions in Fig. 2. 15, it is shown that after implantation and annealing the curves are closer together. In other words, the ratio of the resistance at larger values of s to the smaller values of s is larger

(a)

(b)

Fig. 2. 15 Voltage drop as a function of the current for TLMs for sample 1, after implantation and annealing at (a) 350°C and (b) 450°C .

Fig. 2. 16 Voltage drop as a function of the current for TLMs for sample 2, after implantation.

before implantation than after implantation and annealing. For example, in the central region of the IV curves, the total resistance at $s = 3 \mu\text{m}$ is $\sim 73.35 \%$ of the total resistance at $s = 31 \mu\text{m}$. This ratio is four times the corresponding ratio before implantation and annealing (the total resistance at $s = 3 \mu\text{m}$ is $\sim 18 \%$ of the total resistance at $s = 31 \mu\text{m}$). It can be concluded that the dependence of the total resistance on s has decreased after implantation and annealing. This means that the contact resistance rather than the resistance of the implanted region is the dominant term in Eqn. (2.1). This can be attributed to the fact that the resistance of the P-I-N diode in reverse bias mode dominates the contact resistance. This resistance is very large compared with the resistance of the spacing s .

The total resistance after implantation and annealing for the TLMs of sample 1, sections B and C, for the central (low current) regions of the IV characteristic curves is shown in Fig. 2. 17. Table 2. 4 shows the implantation dose for each wafer section of sample 1. Fig. 2. 17 shows that TLMs of the same section and exposed to the same implantation and annealing conditions were not showing the same behavior. Also the relation between the R_t and s is nonlinear. This behavior may be attributed to the damage occurred in the material under the thin metal contact ($2000 \text{ \AA}$) through which oxygen ions penetrate. This damage affects the behavior of the back-to-back diode structure. For sample 2, the dependence of total resistance on s after implantation is less than it was before implantation, but is still significant. For example, in the central region of the IV curves, the total resistance at $s = 1 \mu\text{m}$ is $\sim 27 \%$ of the total resistance at $s = 25 \mu\text{m}$. This ratio is 2.5 times the corresponding ratio before implantation (the total resistance at $s = 1 \mu\text{m}$ is $\sim 11 \%$ of the total resistance at $s = 25 \mu\text{m}$).

(a)

(b)

(b)

(d)

Fig. 2. 17 Total resistance R_t as a function of contact spacing s for sample 1 after implantation and annealing. The wafer sections are

(a) section B with annealing 350°C

(b) section C with annealing 350°C

(c) section B with annealing 450°C

and (d) section C with annealing 450°C

Table 2. 4 shows the implantation dose for each section.

(a)

(b)

Fig. 2. 18 Total resistance R_t as a function of contact spacing s for sample 2 after implantation. (a) The central section of the IV curve and (b) The edge section of the IV curve. The solid line shows the average total resistance.

The total resistance after implantation for all the TLMs of sample 2 for the central (low current) and positive (high current) regions of the IV characteristic curves is shown in Fig. 2. 18. The solid line shows the average total resistance. The behavior of the different TLMs is the same and the relation between the R_t and s is linear. These better results give an indication that sample 2 has fewer defects than sample 1 and that the back-to-back diode structure is effective. Therefore, sample 2 will be the recommended sample on which the digital optical switches and straight waveguides will be fabricated.

Sample one will not be used for further studies due to the different behavior of the TLMs of the same conditions.

Scatter plots for R_s , R_c , L_t and ρ_c of sample 2 (using the Marlow and Das model [34]) for both low current and high current regions of the IV curves are shown in Figs. 2. 19 –2. 20. The average value for each of R_s , R_c , L_t and ρ_c was shown by a solid line. The maximum, minimum and average values calculated (using the Marlow and Das model [34]) for R_s , R_c , L_t and ρ_c after implantation are given in Table 2. 7 for both the low current and the high current region of the IV curves. The values of R_s , R_c , L_t and ρ_c before implantation are also shown in Table 2. 7 for comparison.

The Reeves and Harrison model [35] was not applicable for the TLMs of sample 1 or 2 after implantation. Calculations using this model give imaginary quantities for R_{sk} , L_{tk} and ρ_{ck} . This can be attributed to the existence of the back-to-back diode structure. The Reeves and Harrison model [35] is used for calculating the contact resistivity of TLMs, which is represented by, at most, one diode. For example R_e is 40 k Ω where as R_c is 17 k Ω . This will make the ratio $R_c \setminus R_e$ in Eqn. (3. 8) become less than one for the first

Fig. 2.19 Scatter plot of measured values of (a) R_s , (b) R_c , (c) L_t and (d) ρ_c after implantation for different TLMs of sample 2 at the central region (low current) of the IV curves. The Marlow and Das model [34] was used in the calculation. The solid line shows the average value. The minimum and maximum values are also indicated.

(a)

(b)

(c)

(d)

Fig. 2.20 Scatter plot of measured values of (a) R_s , (b) R_c , (c) L_t and (d) ρ_c after implantation for different TLMs of sample 2 at the edge region (high current) of the IV curves. The Marlow and Das model [34] was used in the calculation. The solid line shows the average value. The minimum and maximum values are also indicated.

Table 2. 7 The maximum, minimum and average values calculated for R_s , R_c , L_t and ρ_c before and after implantation using the Marlow and Das model [34].

		R_s ($\Omega / \square$)	R_c (Ω)	L_t (μm)	ρ_c ($\Omega - cm^2$)
Maximum	Before Implantation	577.26	21.54	2	2.15×10^{-5}
	After Implantation (Low Current)	169.71 k	17.87 k	6.54	0.0584
	After Implantation (High Current)	60.03 k	6.6 k	6.57	0.022
Minimum	Before Implantation	508.98	8.43	0.82	0.35×10^{-5}
	After Implantation (Low Current)	136.71 k	16.33 k	4.86	0.0401
	After Implantation (High Current)	49.24 k	5.9 k	5.08	0.015
Average	Before Implantation	547.7 ± 25	12.8 ± 1.5	1.18 ± 0.15	0.84×10^{-5} $\pm 0.01 \times 10^{-5}$
	After Implantation (Low Current)	147.74 $\pm 8.34 k$	17.025 $\pm 0.52 k$	5.80 ± 0.5	0.05 ± 0.0057
	After Implantation (High Current)	53.96 $\pm 3.6 k$	6.21 $\pm 0.17 k$	5.79 ± 0.5	0.018 ± 0.002

two values, whilst $\cosh(d / L_{tk})$ cannot be less than one, unless L_{tk} is a complex number. Also the values of R_{sk} become complex. Physically, L_{tk} and R_{sk} can take only positive real values. The complex values of L_{tk} (using the Reeves and Harrison model [35]) can be attributed to the overestimation of the contact resistance, R_c . R_c is no longer represents the contact between the metal electrodes and semiconductor, but rather R_c is dominated by the large resistance of the reverse biased P-I-N diode.

The Reeves and Harrison model [35] is no longer used for further calculations in this thesis because it does not apply to the back-to-back diode structure shown in Fig. 2. 14.

2.7 Summary and Closing Comments

The aim of this Chapter was to determine how effective was the implantation region to isolate the metal electrodes, or contact pads. The behavior of the TLM after implantation is expected to be like a back-to-back diode. The back-to-back diode structure consists of two P-I-N diodes, one in the forward bias mode, which determines the IV characteristics, and the other in the reverse bias mode, whose reverse bias resistance is the dominating factor for determining the contact resistance.

After implantation, the total resistance became very large, in the range of $100 \text{ k } \Omega$ and the contact resistivity was in the range of the $0.05 \text{ } \Omega\text{-cm}^2$. The TLM pad IV plots showed clear diode-like behavior, confirming the isolation implant was successful.

There are two models available to characterize the sheet resistance and contact resistivity of the DOS electrodes using the TLM. The Marlow and Das model is suitable

for comparison between samples before and after implantation, and annealing if applicable while the Reeves and Harrison model gives more accurate values for the contact resistivity. Sample 1 showed bad results after implantation and was not used for further studies of the switch. Sample 2 showed better results and therefore it was used for fabrication of the switch. Before implantation the total resistance of sample 2 versus the spacing between the contact pads was linear and the total resistance was less than 350 Ω . The contact resistivity was in the range of $\sim 10^{-5} \Omega\text{-cm}^2$.

3 Electrical Characterization of the Active Waveguide

3.1 Introduction

A straight waveguide with a metal electrode of length 1400 μm and width 50 μm was used for electrical characterization. The structure is shown in Fig. 3. 1(a).

Waveguides of width 3 μm , 4 μm or 5 μm were studied. The basic structure of the active waveguide section of the switch is a P-I-N diode. Each waveguide has two P-type layers (In_{0.53}Ga_{0.47}As and InP) and two n-type layers (both composed of InP material) of different dopant concentration as shown in Fig. 3. 1(b) and Table 2.2 for sample 2 structures. The layers in between the n- and p-type InP layers are undoped, and are intrinsic layers with total thickness 1.51 μm .

When the P-I-N structure is first formed, holes diffuse from the p side and electrons from the n side into the intrinsic layers where they recombine. This leaves behind a thin layer of exposed negatively charged acceptor ions in the p side and a thin layer of exposed positively charged donor ions in the n side. The intrinsic layer of thickness d separates the two layers. There is an approximately uniform built-in field in the intrinsic layer. The built-in field produces a drift of positive (negative) charge carriers in opposite direction to the diffusion of positive (negative) charge carriers. At equilibrium, the drift current and diffusion current exactly cancel each other. At zero bias, the separation of the two layers of positive and negative charges is fixed.

(a)

(b)

Fig. 3. 1: Straight waveguide and metal electrode. (a) Top view (b) Cross-section

Cap doping concentration is $1 \times 10^{19} \text{ cm}^{-3}$.

The junction capacitance can be calculated from the parallel plate capacitance.

$$C_j = \frac{\epsilon_0 \epsilon_r A}{d} \quad (3.1)$$

where A , ϵ_0 and ϵ_r are the area of the waveguide under the electrode, the permittivity of free space, and the dielectric constant, at low frequency, respectively.

At reverse bias, the spacing between charges increases, but the incremental change is very small with respect to the thickness of the intrinsic region between heavily doped p and n regions. The junction capacitance is essentially constant for zero bias and reverse bias. There is also parasitic capacitance, C_p associated with the metal electrode, underlying dielectric and heavily doped substrate. When forward bias is applied, the p and n regions both inject carriers into the intrinsic region, flooding it with carriers. Electrically, the PIN diode becomes a resistor in parallel with the parasitic electrode capacitance. Together with extra resistance of the wire and transmission line connected to the electrode, a low pass filter with RC time constant is formed. The RC time constant may limit the switching time.

The injected carriers reduce the refractive index by means of the plasma effect to produce the switching action.

3.2 Junction Capacitance

The junction capacitance, C_j , for a straight waveguide can be calculated using Eqn. (3.1). The length is the length of the metal electrode (1400 μm) and the width is the straight waveguide width. The InP dielectric constant, ϵ_r , to be used for capacitance calculations is the low frequency dielectric constant of 12.5 [36]. The separation

between the p and n type layers, d , is $1.51 \mu\text{m}$. ϵ_0 is the permittivity of free space ($\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$).

The junction capacitances, C_j , of the straight waveguides are 0.31 pF, 0.45 pF and 0.56 pF for $3 \mu\text{m}$, $4 \mu\text{m}$ and $5 \mu\text{m}$ waveguides, respectively.

3.3 Electrode Capacitance and Total Capacitance

Most of the electrode area does not cover the active waveguide. The electrode must be much larger for probing purposes. The device surface is planarized prior to electrode metal deposition by SiN_x deposition. A parasitic capacitance is formed by this SiN_x dielectric layer sandwiched between the top metal and the highly doped substrate, as shown in Fig. 3. 2 (a). The electrode capacitance C_p is due to the capacitances C_{p1} of the SiN_x layer and C_{p2} of the undoped InP layer, in series as shown in Fig. 3. 2 (b). Table 3. 1 gives the values for C_{p1} , C_{p2} and C_p for the three waveguides under study. The total capacitance, C_t , which consists of C_j in parallel with C_p is dominated by the parasitic electrode capacitance. The total capacitance is about 3.4 pF.

3.4 Current -Voltage Characterization

The voltage input from a waveform generator was connected to the electrode via a needle probe. A ground wire was connected to the substrate holder for the return current path. A triangular voltage waveform varying between -8 and $+8 \text{ V}$ with period $10 \mu\text{s}$ was used for the measurement. The applied voltage was monitored by a 50Ω probe connected to a channel of a 100 MHz oscilloscope. The PIN diode current was monitored using a current probe connected to the other channel of the oscilloscope. There is a series dc

Fig. 3. 2 Cross section of device in electrode region
 (a) Parasitic electrode capacitance (region 1 and 2)
 (b) Electrode capacitance model

Table 3. 1: Capacitance calculations.

Waveguide Width w_g (μm)	Junction Capacitance C_j (pF)	Capacitor Electrode Width w_e (μm)	Electrode Capacitance			Total Capacitance $C_t = C_j + C_p$ (pF)
			C_{p1} (pF)	C_{p2} (pF)	C_p (pF)	
3	0.31	47	5.67	6.28	3.00	3.31
4	0.45	46	5.55	6.14	2.92	3.37
5	0.56	45	5.43	6.01	2.85	3.41

resistance of about $10\ \Omega$ due to the resistance of the wires connecting the dc power supply to the electrode probe. The IV data was stored for subsequent processing in EXCEL. The resultant IV curves for the experimental waveguides (after removal of the voltage drop across $10\ \Omega$ external resistance) are plotted in Fig. 3. 3.

At reverse bias, the current is negligible and the PIN diode is basically a very large resistor in parallel with the capacitance measured in Section 3. 2.

Under forward bias, the monitored applied voltage is less than the real applied voltage from the pulse generator display. For convenience we will call the monitored applied voltage as waveguide voltage and the applied voltage read from the pulse generator display as the applied voltage. The waveguide (or PIN) potential is 3.3 V, 3.14 V and 2.92 V for $3\ \mu\text{m}$, $4\ \mu\text{m}$ and $5\ \mu\text{m}$ waveguides, respectively. The PIN diode structure exhibits the normal diode exponential current characteristic. The dynamic resistance is different for each size of waveguide. For applied forward voltage greater than about 2 V, the dynamic resistance can be estimated from the inverse slope of tangent lines shown in Fig. 3. 3. The turn-on voltage can also be estimated from the intersection of this tangent line with the voltage axis.

The estimated dynamic resistance is $6.45\ \Omega$, $5.75\ \Omega$ and $3.34\ \Omega$ for the $3\ \mu\text{m}$, $4\ \mu\text{m}$ and $5\ \mu\text{m}$ waveguides, respectively.

The measured turn-on voltage is 0.81 V, 0.70 V and 0.43 V for the $3\ \mu\text{m}$, $4\ \mu\text{m}$ and $5\ \mu\text{m}$ waveguides, respectively. The average turn-on voltage is 0.65 V.

From the above results it is observed that the dynamic resistance, the potential across the waveguide and the turn-on voltage each decreases as the waveguide width increases. This can be explained from the relation of the dc waveguide resistance, R ,

Fig. 3. 3: IV characteristics for the straight waveguide of width 3 μm , 4 μm and 5 μm .

with the waveguide dimensions. R can be written as

$$R = \frac{\rho d}{A} \quad (3.2)$$

where ρ , d and A are the resistivity, thickness and area of the straight waveguide, respectively. The area $A = L W$ where L is the waveguide length and W is the waveguide width.

As the waveguide width is increased, a larger area is available for current injection in the PIN diode. As a result, at a fixed voltage, an increase in waveguide width produces an increase in dc current, a decrease in dc resistance, and also a decrease in dynamic resistance.

3.5 Electrode Pulse Response

The rise time used in this discussion is the time between the points of 10% and 90% of the amplitude.

A 50 MHz bandwidth pulse generator having 7 ns rise time was used to apply 5V triangular pulses, of width 5 μ s and frequency 10 kHz, to the electrode through a 50 Ω cable connected to the needle probe. The needle probe (picoprobe model # 7A) has a 3 dB bandwidth of 350 MHz giving a probe rise time $\tau_{\text{probe}} \sim 1$ ns. Another needle probe and 50 Ω cable connected to the 50 Ω input of a 100 MHz bandwidth (BW) oscilloscope was used to measure the voltage waveform at the electrode. The rise time of the oscilloscope is calculated from $0.35/\text{BW}$ as $\tau_{\text{osc}} = 3.5$ ns.

Consider measurement of the rise time of the 3 μ m waveguide having 6.5 Ω dynamic resistance and capacitance 3.4 pF. The parallel connection of the 50 Ω input

Fig. 3. 4 Waveguide electrical model incorporating waveguide dynamic resistance ($6.5\ \Omega$), waveguide capacitance ($3.4\ \text{pF}$), external resistance ($10\ \Omega$) and cables resistance ($50\ \Omega$, $50\ \Omega$).

probe, 50 Ω output probe, 10 Ω external resistance and PIN diode resistance 6.5 Ω gives total resistance $\sim 5.25 \Omega$. Fig. 3. 4 shows the electrical model of the waveguide from which the RC time constant is calculated. The expected 10% to 90% rise time equals $2.2 RC = 39.3$ ps. Using the similarity between the root mean square deviation σ and the rise time ($\sigma = 0.425\Delta\tau$ where $\Delta\tau$ is the interval between the full width half maximum of a gaussian beam [32]), the measured rise time, τ_{meas} can be given by

$$\tau_{\text{meas}}^2 = \tau_{\text{switch}}^2 + \tau_{\text{osc}}^2 + \tau_{\text{gen}}^2 + 2\tau_{\text{probe}}^2 \quad (3.3)$$

so that

$$\tau_{\text{switch}}^2 = \tau_{\text{meas}}^2 - \tau_{\text{osc}}^2 - \tau_{\text{gen}}^2 - 2\tau_{\text{probe}}^2 \quad (3.4)$$

Using $\tau_{\text{osc}} = 3.5$ ns, $\tau_{\text{gen}} = 7$ ns, $\tau_{\text{probe}} = 1$ ns and $\tau_{\text{meas}} = 13$ ns, τ_{switch} can be calculates, $\tau_{\text{switch}} = 10$ ns.

For the 4 μm and 5 μm waveguides the results are approximately the same since the waveguide dynamic resistance and waveguide capacitance for all the waveguides are approximately the same. Chapter 5 shows how the rise time measurements were made.

3.6 Summary and Closing Comments

The resistance, maximum current, maximum voltage, and the turn-on voltage of the PIN diode under a straight waveguide section were calculated. The resistance, maximum voltage and turn-on voltage each decreases while the maximum current increases as the waveguide width is increased.

The capacitance of the system is due to the junction capacitance and the parasitic capacitance in parallel. The parasitic capacitance is much larger than the junction

capacitance. The total capacitance is about 3.4 pF.

The switch rise time calculated from Eqn (3.4) is ~10 ns while the calculated rise time due to the RC coupling is about 39.3 ps for the different waveguides under study.

4 Optical Characterization of the Active Waveguide

4.1 Introduction

A Fabry- Perot cavity [7, 23, 30, 31, 37] consists of a medium between two mirrors of same, or different, reflectance. Light wave reflections between the two mirrors lead to constructive and destructive interference within the cavity. The result is a series of allowed stationary, or standing, EM waves, or modes. The refractive index and optical loss of the medium in the cavity can be determined by analyzing the maxima and minima, i.e. the fringes, in the transmitted optical wave.

4.2 Fabry-Perot Cavity Equations

Consider a waveguide of length L to have a refractive index n and absorption coefficient α . Also consider the two facets of this waveguide to have the same reflectance R . If I_{incident} is the incident light intensity normal to the facets, then a fraction $(1 - R)$ of it enters the cavity to build up the cavity intensity I_{cavity} . At the other facet, of the same R , a fraction $(1 - R) \exp(-\alpha L)$ of I_{cavity} would leave the cavity as the transmitted intensity $I_{\text{transmitted}}$. I_{cavity} and $I_{\text{transmitted}}$ are calculated as follows:

For an incident beam tilted by an angle θ from the normal to the mirror faces:

$$I_{\text{cavity}} = I_{\text{incident}} \frac{(1 - R)}{(1 - R)^2 + 4 R \sin^2(\phi)} \quad (4.1)$$

$$I_{\text{transmitted}} = I_{\text{incident}} \frac{(1-R)^2}{(1-X)^2 + 4X \sin^2(\varphi)} \quad (4.2)$$

where

$$X = R \exp(-\alpha L) \quad (4.3)$$

$$\varphi = nkL \cos(\theta) \quad (4.4)$$

$$k = \frac{2\pi}{\lambda_o} \quad (4.5)$$

λ_o = wavelength in vacuum

$$\text{and } \lambda = \frac{\lambda_o}{n} = \text{wavelength in medium} \quad (4.6)$$

For normal incidence, $\theta = 0^\circ$, I_{cavity} and $I_{\text{transmitted}}$ are maximum when

$$\sin(nkL) = 0 \quad (4.7)$$

That is

$$nk_m L = m\pi \quad \text{or} \quad L = \frac{m\lambda_m}{2}, \quad m = 1, 2, 3, \dots \quad (4.8)$$

For clarity, subscript m has been added to k_m and λ_m to indicate the m^{th} mode. The maximum values of I_{cavity} and $I_{\text{transmitted}}$ are given by

$$I_{\text{cavity_max}} = I_{\text{incident}} \frac{(1-R)}{(1-X)^2} \quad (4.9)$$

$$I_{\text{transmitted_max}} = I_{\text{incident}} \frac{(1-R)^2}{(1-X)^2} \quad (4.10)$$

For normal incidence, $\theta = 0^\circ$, I_{cavity} and $I_{\text{transmitted}}$ are minimum when

$$\sin(nkl) = \pm 1 \quad (4.11)$$

The minimum values of I_{cavity} and $I_{\text{transmitted}}$ are given by

$$I_{\text{cavity_min}} = I_{\text{incident}} \frac{(1-R)}{(1+X)^2} \quad (4.12)$$

$$I_{\text{transmitted_min}} = I_{\text{incident}} \frac{(1-R)^2}{(1+X)^2} \quad (4.13)$$

4.2.1 $\Delta \lambda$ Calculation

From Eqn.(4.8), the corresponding frequency ν_m of the m^{th} mode is the m^{th} resonant frequency of the cavity [32 and 37],

The length L can fit multiple number (m) of $\lambda/2$. This can be written as

$$m = \frac{2 n(\lambda_m) L}{\lambda_m} \quad (4.14)$$

For the following mode ($m+1$) Eqn. (4.14) is written as

$$m+1 = \frac{2 n(\lambda_{m+1}) L}{\lambda_{m+1}} \quad (4.15)$$

By subtracting Eqn. (4.14) from Eqn. (4.15) and dividing by $2L$, we get

$$\frac{1}{2L} = \frac{n(\lambda_{m+1}) \lambda_m + n(\lambda_m) \lambda_{m+1}}{\lambda_m \lambda_{m+1}} \quad (4.16)$$

$n(\lambda_{m+1})$ can be written as

$$n(\lambda_{m+1}) = n(\lambda_m) + \frac{dn}{d\lambda} (\lambda_{m+1} - \lambda_m) \quad (4.17)$$

and

$$\lambda_{m+1} \lambda_m = \lambda_m^2 = \lambda_{m+1}^2 = \lambda^2 \quad (4.18)$$

By substituting into Eqn (4.16) we get

$$\frac{\lambda_m^2}{2L} = - \left[n(\lambda_m) - \lambda_m \frac{dn}{d\lambda} \right] (\lambda_{m+1} - \lambda_m) \quad (4.19)$$

The group index of refraction (n_g) can be written as

$$n_g = n - \lambda \frac{dn}{d\lambda} \quad (4.20)$$

By substituting into Eqn (4.19) we get

$$\Delta\lambda_m = (\lambda_{m+1} - \lambda_m) = - \frac{\lambda_m^2}{2n_g L} \quad (4.21)$$

The approximation $\lambda_{m+1} \lambda_m = \lambda_m^2$ is valid for large m , say greater than 10. In this work, $L > 600 \lambda$, and as a result $m > 600$. We can neglect the subscript “ m ” because the range of wavelengths is small compared with the mean value of wavelength.

4.2.2 Group Index of Refraction Calculation

By knowing λ , L and $\Delta\lambda$ the index of refraction, n , can be calculated.

$$n_g = \frac{\lambda^2}{2L \Delta\lambda} \quad (4.22)$$

4.2.3 Reflectance Calculation

Reflectance, R , is the ratio of the reflected power to the incident power. As the light propagates through the interface between the medium and air, the reflectance of the end facets, R , of the medium can be calculated from the Fresnel's equation [37 and 38] as follows,

$$R = \left(\frac{n-1}{n+1} \right)^2 \quad (4.23)$$

The reflection coefficient or reflectivity, r , is the ratio of the reflected electric field amplitude to the incident electric field amplitude. Therefore, $r = \sqrt{R}$.

4.2.4 Absorption Coefficient and Loss Calculations

The ratio of the maximum, $I_{\max}$, and minimum, $I_{\min}$, of the transmitted light intensity of the Fabry-Perot fringes can be measured and used in the calculations of the absorption coefficient, α , of the medium between the mirrors [7, 30, 31]. By solving Eqns. (4.10) and (4.13), the absorption coefficient α (Neper / m) can be calculated from

$$-\alpha L = \ln \left(\frac{1 - \sqrt{1 - \gamma^2}}{\gamma R} \right) \quad (4.24)$$

where L is in meters and

$$\gamma = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (4.25)$$

The absorption coefficient α_{dB} (dB/ m) is given by

$$\alpha_{\text{dB}} = 4.34 \alpha \quad (4.26)$$

The loss, in dB, of the waveguide of length L is then

$$\Gamma_{\text{wg}} = \alpha_{\text{dB}} L \quad (4.27)$$

4.2.5 Fiber-Waveguide Coupling Loss Calculation

Let I_{in} and I_{out} be the input and output intensities at the input and output of the

input and output fibers, respectively. The total loss, Γ_t in dB can be calculated as follows,

$$\Gamma_t = \Gamma_{if} + \Gamma_{cif} + \Gamma_{wg} + \Gamma_{cof} + \Gamma_{of} \quad (4.28)$$

where Γ_{if} , Γ_{cif} , Γ_{cof} and Γ_{of} are the loss, in dB, in the input fiber, input fiber-waveguide coupling loss, waveguide-output fiber coupling loss and output fiber loss. Γ_{if} , Γ_{of} and are known and easy to measure. Γ_{wg} is calculated as shown in section 4.2.3. Since the input and output fibers are identical and the two facets of the waveguide are assumed to be identical, then it is assumed the coupling losses are the same, i.e. $\Gamma_{cif} = \Gamma_{cof} = \Gamma_{cf}$

$$\Gamma_{cif} = \Gamma_{cof} = \Gamma_{cf} = \Gamma_t - (\Gamma_{if} + \Gamma_{wg} + \Gamma_{of}) = \Gamma_t - (\Gamma_{wg} + 2\Gamma_f) \quad (4.29)$$

where $\Gamma_{if} = \Gamma_{of} = \Gamma_f$. Knowing Γ_t , Γ_{cf} can be calculated from Eqn. (4. 23). Γ_t can be calculated as follows

$$\Gamma_t = 10 \log \left(\frac{I_{out}}{I_{in}} \right) \quad (4.30)$$

In this chapter, we will calculate the α , α_{dB} , Γ_{wg} and coupling loss, Γ_{cf} , for the straight waveguides, with and without metal, of different lengths by measuring the $\Delta\lambda$, I_{max} and I_{min} . The wavelength of interest is near 1550 nm.

4.3 Experimental Setup for Fabry-Perot Measurements

The experimental setup is shown in Fig. 4.1. The first step was to couple light into and out of the waveguide in the desired TE or TM waveguide mode. The setup shown in Figure 4. 1(a) was used for the initial waveguide alignment. Single mode (SM) Polarization maintaining (PM) fiber was used for both the input and the output fibers. Laser light was delivered to the lensed fiber (the input fiber) through a half wave plate, which was used to control the

polarization. The input lensed fiber was mounted on an XYZ position stage. This lensed fiber worked as a concave lens to focus the laser beam onto the end facet of the straight waveguide mounted on an XYZ position stage. As shown in Fig. 4.1(a), the microscope objective was mounted on another XYZ position stage in front of the output facet to collect the output beam and deliver a wider beam to an infrared (IR) video camera connected to a monitor. The X, Y and/or Z knobs of the position stage of the microscope objective were adjusted so that a clear spot appeared on the monitor. A cubic polarizer was placed in the path of the output beam before reaching the infrared (IR) video camera. This polarizer was adjusted to pass the TM mode. The input half wave plate was rotated until the brightest spot appeared on the monitor. Then a photo detector was placed in the path of the beam between the polarizer and the IR camera. The half wave plate was rotated to get the maximum output power. The output power in this case is in the waveguide TM mode. By rotating the half wave plate 45° , the polarization became TE mode and the output power was minimum. The half wave plate was rotated back to the TM position and the microscope objective was replaced by a lensed fiber (the output fiber) to deliver the output power directly to the photo detector as shown in Fig. 4. 1(b). The output fiber was aligned with the output facet of the waveguide until a maximum power was reached. A signal generator (sinusoidal waveform, 1 kHz, 4 V peak) was connected to the input of a lock-in amplifier and also to the modulation input of the tunable laser device as shown in Fig. 4.1(b). Care was used not to disturb the PM fiber alignment just discussed. The photo-detector at the output fiber was connected to the lock-in amplifier to boost the detected signal. The wavelength data from the laser and the corresponding optical power data from the lock-in amplifier were the input data to the computer. The computer ran a program called optolab to plot the power received from the

(a)

(b)

Fig. 4. 1 The experimental setup for Fabry-Prot measurements

(a) Setup for alignment the input fiber with the waveguide and adjusting the polarization mode.

(b) Setup for measurement of the Fabry-Perot fringes.

lock-in amplifier as a function of the wavelength received from the tunable laser. The wavelength was stepped from 1445 nm to 1555 nm with 0.1 nm step size, or from 1549 nm to 1551 nm with step size 0.001 nm. The data were saved as EXCEL files for later processing and plotting.

After obtaining and saving the data for the TM mode, the half wave plate was rotated 45° and the data for the TE mode was measured and saved.

The above procedure was repeated for different straight waveguides of various widths either with or without metal electrodes. Therefore, twelve plots were produced for further calculation as shown in the next sections.

4.4 Fabry-Perot Results for Straight Waveguides

Figs. 4.2 and 4. 3 show the Fabry-Perot fringes for straight waveguides of widths $3\ \mu\text{m}$ without metal electrodes for TE and TM modes. Figs.4. 4 and 4. 5 show the Fabry-Perot fringes for straight waveguides of widths $3\ \mu\text{m}$ with metal electrodes for TE and TM modes. The plots for the $4\ \mu\text{m}$ and $5\ \mu\text{m}$, waveguides were similar to the ones shown for the $3\ \mu\text{m}$ waveguides. I_{max} , I_{min} and $\Delta\lambda$ used for calculations are shown in Figs.4.2 - 4.5. The waveguide length is measured to be $2.2\ \text{mm} \pm 0.01\ \text{mm}$ using a microscope having an eyepiece objective with a scale in micrometers. From these data n , R , α and Γ were calculated.

4.4.1 $\Delta\lambda$ Results

For all the twelve figures, $\Delta\lambda$ was measured between every two adjacent maxima. All

Fig. 4. 2 Fabry-Perot fringes for straight waveguide of width $3\ \mu\text{m}$ without metal electrode (TE-mode). For each point corresponding to I_{max} , the next point corresponding to I_{min} is used for the calculation of γ . $\Delta\lambda$ is shown in the figure.

Fig. 4. 3 Fabry-Perot fringes for straight waveguide of width $3\ \mu\text{m}$ without metal electrode (TM-mode). For each point corresponding to I_{max} , the next point corresponding to I_{min} is used for the calculation of γ . $\Delta\lambda$ is shown in the figure.

Fig. 4. 4 Fabry-Perot fringes for straight waveguide of width 3 μm with metal electrode (TE-mode). For each point corresponding to I_{max} , the next point corresponding to I_{min} is used for the calculation of γ . $\Delta\lambda$ is shown in the figure.

Fig. 4. 5 Fabry-Perot fringes for straight waveguide of width 3 μm with metal electrode (TM-mode). For each point corresponding to I_{max} , the next point corresponding to I_{min} is used for the calculation of γ . $\Delta\lambda$ is shown in the figure.

measurements produced the same result, 0.15 nm, with an error of 0.001 nm.

$$\Delta\lambda = 0.15 \pm 0.001 \text{ nm} \quad (4.31)$$

The uncertainty in $\Delta\lambda$ is due to the 0.001 nm step size used for tuning the wavelength.

4.4.2 Group Index of Refraction Results

From Eqn. (4.22), an approximate value for n can be calculated. At wavelength 1550 nm, using $L = 2.2$ mm and $\Delta\lambda = 0.15$ nm, n_g is calculated as 3.64. This result is in agreement with the calculated value using the waveguide mode solver(3.65).

4.4.3 Reflectance Results

Since the light beam is aligned to propagate in the InGaAsP layer, we can use the refractive index of the InGaAsP to calculate the reflectance (R). The refractive index of the InGaAsP is 3.37. Eqn.(4.23) is used to calculate R . $R = 29.4\%$

4.4.4 Absorption Coefficient Results for Straight Waveguides without Metal Electrodes

$I_{\max}$ and $I_{\min}$ were measured for waveguides without metal electrode of 3 μm , 4 μm and 5 μm width for TE and TM modes. The loss coefficient α_{dB} was calculated using Eqns. (4.24) - (4.27). Fig. 4. 6 shows the scatter plot of the average absorption coefficient, α_{dB} , as calculated from the R values, versus the waveguide width for TE and TM modes of the waveguide with and without metal electrode.

The Fabry-Perot measurements for the TE and TM modes were done under the same

alignment conditions and the interval between each measurement was from 1 to 2 minutes.

For the TM mode, the average absorption coefficient, α_{dB} , is 16.3 dB/cm, 18 dB/cm and 17.3 dB/cm for 3 μm , 4 μm and 5 μm width waveguide, respectively. The 4 μm width waveguide shows a little higher absorption coefficient than the other two waveguides. α_{dB} has to be the same for different waveguide widths. These changes in α_{dB} are most probably owing to the non-perfect end facets or non-homogeneous loss distribution after cleaving the substrate [30]. The effect of higher order modes can also change the loss for different waveguide widths. For the TE mode, the absorption coefficient α_{dB} is 5.1 dB/cm, 8.5 dB/cm and 11.3 dB/cm for 3 μm , 4 μm and 5 μm width waveguide, respectively. The 4 μm width waveguide shows medium values between the 3 μm and 5 μm width waveguides. The changes in α_{dB} for different waveguide widths may be attributed to the contribution of the higher order modes in the output power, as we will show later. It is clear that the TE mode propagates with lower loss than the TM mode. The experimental data also indicate that the absorption coefficient varies with waveguide width faster for the TE mode than for the TM mode.

4.4.5 Absorption Coefficient Results for Straight Waveguides with Metal Electrodes

The procedure mentioned in section 4.4.4 to obtain α_{dB} was repeated for straight waveguides with metal electrodes. The average values of α_{dB} for TE and TM modes of 3 μm , 4 μm and 5 μm width waveguide are shown in Figure 4. 6.

The Fabry-Perot measurements for the TE and TM modes were done under the same

Fig. 4. 6 The scatter plot of the average absorption coefficient, α_{dB} (as calculated from the R values) versus the waveguide width for TE and TM modes of the waveguide with and without metal electrode.

alignment conditions and the interval between each measurement was from 1 to 2 minutes.

For the TM mode, the average absorption coefficient, α_{dB} , is 24.4 dB/cm, 19.4 dB/cm and 19.3 dB/cm for 3 μm , 4 μm and 5 μm width waveguide, respectively. The 4 μm width waveguide shows approximately the same absorption coefficient as the 5 μm width waveguide. This is most probably owing to the roughness of the waveguide width edges. The 3 μm waveguide has highest loss because part of the light is absorbed at the rough edges of the width. With increasing the width, the part of light absorbed at the rough edges decreases and contribution of the light propagating through the waveguide increases. The contribution of higher order modes can affect the accuracy of the results. For the TE mode, the absorption coefficient α_{dB} is 7.09 dB/cm, 7.10 dB/cm and 7.13 dB/cm for 3 μm , 4 μm and 5 μm width waveguide, respectively. The absorption coefficient values are approximately the same for different waveguide widths. It is clear that the TE mode propagates with lower loss than the TM mode.

4.5 Absorption Coefficient Simulation

The Apollo Photonic Solutions Suite (APSS) was used as an optical mode solver. The structure and dimensions of the straight waveguide layers were input to the simulator. The refractive index, n , for each layer of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ as a function of donor, N , and acceptor, P , concentrations was given by [33]

$$n = n_o - \left(\frac{e \lambda}{\pi c} \right) \frac{1}{8 \epsilon_o n_o} \left(\frac{N}{m_e} + \frac{P}{m_h} \right) \quad (4.32)$$

where

$$n_o = 3.167 + 0.314 y \quad (4.33)$$

$$m_e = (0.08 - 0.039y) m_o \quad (4.34)$$

$$m_{hh} = (0.56 - 0.22y + 0.11y^2) m_o \quad (4.35)$$

$$m_{lh} = (0.12 - 0.092y + 0.024y^2) m_o \quad (4.36)$$

$$m_h = 2 \left(\frac{m_{lh} \cdot m_{hh}}{m_{lh} + m_{hh}} \right) \quad (4.37)$$

Eqn. (4.33) is used to calculate the refractive index, n_o , of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ without doping as a function of the arsenic concentration, y [38, 39]. Eqns.(4.34)-(4.36) are used to calculate m_e , m_{hh} and m_{lh} , respectively, as a function of electron rest mass, m_o , and y [41]. m_h was calculated from Eqn.(4.37) [42].

For InP layers, $x = 0$ and $y = 0$ and for InGaAsP, $x = 0.27$ and $y = 0.41$. The refractive index n can be calculated from Eqn.(4.32) with the help of Eqns. (4.33)-(4.37).

For a straight waveguide with metal two extra layers are added. These two layers are InGaAs, $x = 0.27$ and $y = 1$, and metal layer, Ti/Pt/Au. The refractive index of the metal is

$$n = 4.04 - j3.82 \quad (4.38)$$

Table 4. 1 shows the refractive index of each layer. The straight waveguide without metal does not have the first two layers. The wavelength used in the simulation is 1550 nm. The effective index method, EIM, is the numerical method used in the calculations. In this method the cross section of the waveguide was consisting of 150 horizontal and 150 vertical lines to form a mesh. The APSS simulator is then run to find the value of the electric field at different intersection points and to calculate the effective refractive index and absorption coefficient for each available polarization and spatial mode.

The simulation was run for the fundamental mode, 00 mode, and the first order mode,

Table 4. 1: The refractive index before doping, n_0 , and after doping, n , for each layer of the straight waveguide structure.

Layer	n_0	n
Metal Electrode (Ti/Pt/Au)	$4.04 - j3.82$	
InGaAs (p-type, $1 \times 10^{19} \text{ cm}^{-3}$)	3.411	$3.3779 - j3.61 \times 10^{-2}$
InP (p-type, $5 \times 10^{17} \text{ cm}^{-3}$)	3.167	$3.166142 - j7 \times 10^{-5}$
InP	3.167	
InGaAsP	3.37	
InP	3.167	
InP (n-type, $1 \times 10^{18} \text{ cm}^{-3}$)	3.167	$3.1628 - j3.56 \times 10^{-5}$
InP (n-type, $8 \times 10^{18} \text{ cm}^{-3}$)	3.167	$3.1331 - j5.506 \times 10^{-4}$

The first two layers, metal electrode and InGaAs, are not present for the waveguide without metal electrode.

Table 4. 2: Experimental and calculated values of absorption coefficient α_{dB} , in dB/cm, for different straight waveguides without and with metal electrodes.

Waveguide Width	Polarization	Waveguide Without Metal			Waveguide With Metal		
		Experimental	Calculated		Experimental	Calculated	
			00 Mode	10 Mode		00 Mode	10 Mode
3 μm	TM	-16.317	0.0	N/A	-24.446	-9.51	N/A
	TE	-5.069	+0.39	N/A	-7.089	-1.06	N/A
4 μm	TM	-17.983	0	-303.9	-19.427	-12	-2.46
	TE	-8.494	+0.25	-1731.6	-7.103	-1.41	-5.43
5 μm	TM	-17.325	0	-114.4	-19.32	-13.03	-5.28
	TE	-11.300	+0.18	-13000	-7.129	-1.76	-146.8

10 mode, to calculate the refractive index. Higher-order modes are not significant. Fig. 4. 7 shows the electric field amplitude of the fundamental mode for the 3 μm width waveguides with metal electrode for the TE polarization. The simulator did not produce a first order mode for the 3 μm waveguide. For 4 μm and 5 μm , the first order results were of significant value. Figure 4.10 shows the first-order mode for the 5 μm width waveguide with metal for the TE Polarization. It can be shown from Fig. 4. 7 that the fundamental mode is propagating in the core while as Fig. 4.8 shows that most of the power of the first-order mode is propagating in the layers below the core. Therefore, if the first-order mode (compared with the fundamental mode) has enough power or absorption coefficient comparable to that of the fundamental mode, it will contribute (during the fiber waveguide coupling) to the output power. Table 4. 2 shows the experimental and calculated values of absorption coefficient α_{dB} , in dB/cm, for different straight waveguides without and with metal electrodes in the TE and TM polarization state. For waveguide without metal, the calculated values for the TE and TM polarization modes of the fundamental mode are either negligible or a small positive number. Since the imaginary part of the refractive index is 4 to 5 orders of magnitude less than the real part, there is significant uncertainty in the loss calculations using the numerical methods.

The resultant electric field of the fundamental and first order modes of a wave propagating in the positive z – direction can be written as

$$E_{\text{total}}(z, t) = E_{00}(z, t) + E_{10}(z, t) \quad (4.39)$$

$$E_{00}(z, t) = A \exp(-\alpha_{00} z) \exp[j(\omega t - k_{00} z)] \quad (4.40)$$

$$E_{10}(z, t) = B \exp(-\alpha_{10} z) \exp[j(\omega t - k_{10} z)] \quad (4.41)$$

where A and B are the amplitudes for the fundamental and first order modes, respectively,

Fig. 4. 7 Electric field amplitude for the fundamental mode wave propagating into a straight waveguide with metal electrode. The propagating wave has a TE polarization state. The waveguide width is (a) $3\ \mu\text{m}$ and (b) $5\ \mu\text{m}$.

Fig. 4. 8 Electric field amplitude for the first-order mode wave propagating into a straight waveguide with metal electrode. The propagating wave has a TE polarization state. The waveguide width is 5 μm .

while as α_{00} and α_{10} are the absorption coefficient, in Neper / cm, for the fundamental and first order modes, respectively. The angular frequency is ω ; k_{00} and k_{10} are the propagation constants ($k_{00} = 2\pi/\lambda_{00} = 2\pi n_{00}/\lambda_0$ and $k_{10} = 2\pi/\lambda_{10} = 2\pi n_{10}/\lambda_0$). The wavelengths in vacuum, for the fundamental mode and for the first-order mode are λ_0 , λ_{00} and λ_{10} , respectively. The effective refractive indices for the fundamental and first-order modes are n_{00} and n_{10} , respectively. If we try to write E as

$$E(z, t) = C \exp(-\alpha z) \exp[j(\omega t - k z)] \quad (4.42)$$

we will find that a simple relation for C, α and k is difficult to reach. In other words, each of C, α and k is dependent on A, B, α_{00} , α_{10} , k_{00} and k_{10} . If both modes are present, a beat pattern is produced which complicates the Fabry-Perot fringe measurement. This beat pattern can be seen in Figs. 4. 2 - 4. 5.

Although we will not get into the mathematical complexity of calculating the equivalent absorption coefficient, it can be concluded from Eqns. (4.39) – (4.42) that if the amplitudes A and B are comparable, then the mode of larger absorption coefficient will vanish faster and the waveguide can be considered as supporting one mode. This can be true in case of the 3 μm width waveguide, which supports only the fundamental mode. However, the experimental values are much larger than calculated values for both kinds of waveguides, with or without a metal electrode.

4.6 Fiber-Waveguide Coupling Loss Results

The powers I_{in} and I_{out} are measured at the input of the input fiber, and the output of the output fiber, respectively. The input power to the input fiber is 0. 9 mW and the output

Table 4.3: The total loss, Γ_t , waveguide loss, Γ_{wg} , and coupling loss, Γ_{cf} , for different straight waveguides without metal electrodes.

Waveguide	I_{out} (mW)	Γ_t (dB)	Γ_{wg} (dB)	Γ_{cf} (dB)
3 μ m, TM	14.5	17.93	3.25	7.34
			3.9	7.02
average			3.45	7.24
4 μ m, TM	17.5	17.11	3.52	6.8
			4.15	6.48
average			3.95	6.58
5 μ m, TM	15	17.78	3.32	7.23
			4.03	6.88
average			3.66	7.06
3 μ m, TE	17.5	17.11	0.78	8.17
			1.87	7.62
average			1.98	7.57
4 μ m, TE	14	18.08	1.41	8.34
			2.92	7.58
average			1.87	8.11
5 μ m, TE	7.5	20.79	2.15	9.32
			2.62	9.09
average			2.46	9.17

The first, second and third number in each cell are the lowest, highest and average value. $n = 3.37$, $R = 0.294$ and $L = 2.2$ mm. The input power $I_{in} = 0.9$ mW

Table 4.4: The total loss, Γ_t , waveguide loss, Γ_{wg} , and coupling loss, Γ_{cf} , for different straight waveguides with metal electrodes.

Waveguide	I_{out} (mW)	Γ_t (dB)	Γ_{wg} (R) (dB)	Γ_{cf} (R) (dB)
3 μ m, TM	11.2	19.05	4.41	7.32
			6.83	6.11
average			5.25	6.90
4 μ m, TM	15	17.78	3.83	6.98
			4.5	6.64
average			4.14	6.82
5 μ m, TM	16.5	17.37	3.60	6.89
			4.63	6.37
average			4.12	6.63
3 μ m, TE	18.5	16.87	1.08	7.90
			1.76	7.56
average			1.42	7.73
4 μ m, TE	20.5	16.42	1.97	7.23
			1.71	7.36
average			1.42	7.50
5 μ m, TE	18	16.99	1.08	8.00
			1.98	7.51
average			1.43	7.78

The first, second and third number in each cell are the lowest, highest and average value. $n = 3.37$, $R = 0.294$ and $L = 2.2$ mm. The input power $I_{in} = 0.9$ mW

Fig. 4. 9 The scattering plot of the average coupling loss, Γ_{cf} (as calculated from the R values) versus the waveguide width for TE and TM modes of the waveguide with and without metal electrode.

Fig. 4. 10 The scattering plot of the average waveguide loss, Γ_{wg} (as calculated from the R values) versus the waveguide width for TE and TM modes of the waveguide with and without metal electrode.

from the input fiber is 0.84 mW. The loss in the input fiber is 0.3 dB. The loss in the output fiber is the same, i.e. $\Gamma_{if} = \Gamma_{of} = \Gamma_f = 0.3$ dB. The output powers, I_{out} , and the total loss, Γ_t , as calculated from Eqn. (4.30), for every waveguide with TM and TE modes are shown in Tables 4.3 and 4. 4.

Figs. 4. 9 and 4. 10 show the scatter plots of the average coupling loss, Γ_{cf} , and average waveguide loss, Γ_{wg} , (as calculated from the R values) versus the waveguide width for TE and TM modes of the waveguide with and without metal electrode. Γ_{cf} was calculated by substituting the values of Γ_t , Γ_f and Γ_{wg} into Eqn. (4.29). The values of Γ_{cf} are also shown in Tables 4. 3 and 4. 4. From the Tables 4. 3 and 4. 4, the TE mode has larger waveguide loss than the TM mode. A large part of the total loss is due to the coupling between the waveguide and the fiber. It is important to achieve good coupling between the fundamental (00) waveguide mode and the lensed fiber.

4.7 Summary and Closing Comments

The aim of this Chapter is to calculate the waveguide loss using the Fabry-Perot technique.

A straight section of waveguide with two cleaved ends was modeled as a Fabry-Perot cavity. From the fringe pattern in the transmitted optical signal, the waveguide loss was calculated. For the TM mode the loss was 15 dB/cm to 18 dB/cm without metal electrode present, and 18.4 dB/cm to 24.5 dB/cm with metal electrode present. For the TE mode the loss was from 4 dB/cm to 11.5 dB/cm without metal electrode present, and 6 dB/cm to 7.5 dB / cm with metal electrode present.

Only the fundamental (00) mode can propagate in the 3 μm wide waveguide.

However, in the 4 μm wide and 5 μm wide waveguides, the first-order (10) mode can also propagate. This mode has a maximum lobe in the substrate below the ridge. When coupling to fiber for experimental measurement, one must be sure to couple to the (00) mode.

5 Optical Switching

5.1 Introduction

Consider a straight waveguide, which has a metal electrode over a portion of its length. When a positive voltage is applied to the electrode, charge carriers are injected into the intrinsic region of the PIN diode under the electrode. As a result, the refractive index and absorption coefficient of the waveguide are altered under the electrode. The waveguide is divided into three parts as shown in Fig. 5. 1. The sections without metal are parts 1 (input) and 3 (output); the central section with metal is part 2. Each section has length L_i , refractive index n_i , end facet reflectance R_i , and absorption coefficient α_i , with $i = 1, 2$ or 3 . In our design, the parameters with $i = 1$ and 3 are identical.

The direct relationships used in Chapter 4 are no longer simple to write. It is better to write the relationships using a matrix formulation [38, 43]. The problem of transmission of electromagnetic radiation through the straight waveguide can be solved using the 2×2 matrix method. The absorption coefficient, α , will be ignored for simplicity.

The electric field that satisfies Maxwell's equations has the form [38, 43],

$$E = E(z) \exp(i\omega t) \quad (5.1)$$

where ω , t and z are the angular frequency ($= 2\pi f$ where f is the frequency in Hz), the time and distance along the z direction. The electromagnetic wave is assumed to propagate in the z -direction and the electric field is either TE or TM polarization mode. The electric field distribution, $E(z)$, can be written as

Fig. 5. 1 The straight waveguide and its parts when a potential difference, forward biasing, is applied on the middle part

$$E(z) = \begin{cases} A_{\text{in}} \exp(-ik_{\text{in}}z) & z < 0 \\ A_1 \exp(-ik_1z) + B_1 \exp(ik_1z) & 0 < z < z_1 \\ A_2 \exp(-ik_2(z-z_1)) + B_2 \exp(ik_2(z-z_1)) & z_1 < z < z_2 \\ A_3 \exp(-ik_3(z-z_2)) + B_3 \exp(ik_3(z-z_2)) & z_2 < z < z_3 \\ A_{\text{out}} \exp(-ik_{\text{out}}(z-z_3)) & z_3 < z \end{cases} \quad (5.2)$$

k_j , A_j and B_j are the wave vectors, the amplitude of the wave traveling in the positive z -direction and the amplitude of the wave traveling in the negative z -direction, respectively.

We have

$$k_j = n_j \frac{\omega}{c}, \quad j = \text{in}, 1, 2, 3 \text{ and out} \quad (5.3)$$

where

$$n_1 = n_3 \quad \text{and} \quad n_2 = n_1 + \Delta n \quad (5.4)$$

and

$$z_1 = L_1, z_2 = L_1 + L_2 \quad \text{and} \quad z_3 = L_1 + L_2 + L_3 \quad (5.5)$$

$$L_1 = L_3 = 400 \mu\text{m} \quad \text{and} \quad L_2 = 1400 \mu\text{m} \quad (5.6)$$

The effective refractive index along the straight waveguide can be written as

$$n(z) = \begin{cases} 1 & z < 0 \\ n_1 & 0 < z < L_1 \\ n_2 & L_1 < z < L_1 + L_2 \\ n_3 & L_1 + L_2 < z < L_1 + L_2 + L_3 \\ 1 & L_1 + L_2 + L_3 < z < L_1 \end{cases} \quad (5.7)$$

A_j and B_j can be written in terms of A_{j+1} and B_{j+1} as follows [38, 39]

$$\begin{pmatrix} A_{\text{in}} \\ B_{\text{in}} \end{pmatrix} = D_{\text{in}}^{-1} D_1 \begin{pmatrix} A_1 \\ B_1 \end{pmatrix} \quad (5.8)$$

$$\begin{pmatrix} A_j \\ B_j \end{pmatrix} = P_j D_j^{-1} D_{j+1} \begin{pmatrix} A_{j+1} \\ B_{j+1} \end{pmatrix} \quad j = 1, 2, 3 \text{ and for } j = 3, j+1 = \text{out} \quad (5.9)$$

and

$$\begin{pmatrix} A_{in} \\ 0 \end{pmatrix} = D_{in}^{-1} D_1 P_1 D_1^{-1} D_2 P_2 D_2^{-1} D_3 P_3 D_3^{-1} D_{out} \begin{pmatrix} A_{out} \\ B_{out} \end{pmatrix} \quad (5.10)$$

where

$$D_{in} = D_{out} = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad (5.11)$$

$$D_j = \begin{pmatrix} 1 & 1 \\ n_j & -n_j \end{pmatrix}, \quad j=1, 2, 3 \quad (5.12)$$

and

$$P_j = \begin{pmatrix} \exp(k_j L_j) & 0 \\ 0 & \exp(-k_j L_j) \end{pmatrix}, \quad j=1, 2, 3 \quad (5.13)$$

These equations are valid for both TE and TM modes since the waves are incident normal to the waveguide facets (i.e. the angle of incidence $\theta = 0^\circ$). The effect of reflection from the input and output fibers to the waveguide and from the waveguide to the fibers is neglected and, therefore, it can be considered that $B_{in} = B_{out} = 0$.

It is preferable to write the output amplitude as a function of the input amplitude.

Eqns. (5.8) to (5.10) can be inverted to give

$$\begin{pmatrix} A_1 \\ B_1 \end{pmatrix} = D_1^{-1} D_{in} \begin{pmatrix} A_{in} \\ B_{in} \end{pmatrix} \quad (5.14)$$

$$\begin{pmatrix} A_{j+1} \\ B_{j+1} \end{pmatrix} = D_{j+1}^{-1} D_j P_j^{-1} \begin{pmatrix} A_j \\ B_j \end{pmatrix} \quad j=1, 2, 3 \text{ and for } j=3, j+1 = \text{out} \quad (5.15)$$

$$\begin{pmatrix} A_{out} \\ B_{out} \end{pmatrix} = D_{out}^{-1} D_3 P_3^{-1} D_3^{-1} D_2 P_2^{-1} D_2^{-1} D_1 P_1^{-1} D_1^{-1} D_{in} \begin{pmatrix} A_{in} \\ 0 \end{pmatrix} \quad (5.16)$$

The above equations show that the output signal with bias applied to the electrode

Fig. 5. 2 Simulation figures of the propagation of light into theY-junction's branches. Y-junction in (a) and (b) is without applying a bias voltage and in (c) and (d) is with applying bias to the upper (left) branch. The software used for simulation is APSS and the method used for calculations is BPM method. The branching angle of the switch is 0.9° . The length, width of the branch, separation between output ports and gap between the electrodes are $1400\text{ }\mu\text{m}$, $3\text{ }\mu\text{m}$, $20\text{ }\mu\text{m}$ and $1\text{ }\mu\text{m}$, respectively.

($n_1 = n_3$ and $n_1 \neq n_2$) is different than the output when no bias is applied ($n_1 = n_2 = n_3$).

A forward bias voltage is applied so that carriers, both holes and electrons, are injected into the waveguide to produce a change in the refractive index. As a result the output power will be altered during the time of voltage application. The refractive index will decrease when the voltage is applied, i.e. $\Delta n = n_2 - n_1$ is negative.

For the Y-switch, switching is due to the index change. When forward bias was applied on one of Y switch's branches, carriers were injected into this branch causing a decrease in the branch refractive index. Then the light was guided into the other branch. Fig. 5. 2 shows the simulation of the light propagating into the Y-switch without and with a forward bias voltage to the upper (left) branch. The software used for simulation is Apollo Photonic Solutions Suite (APSS). The Beam Propagation Method (BPM) is the method used in the calculations. Simulation was done for a Y-switch of branching angle $A = 0.9^\circ$. The length of the switch is $1400 \mu\text{m}$ and the width of the branch is $3 \mu\text{m}$. The separation between output ports is $20 \mu\text{m}$ and the gap between the electrodes is $1 \mu\text{m}$.

5.1.1 Calculation of the Change in Refractive Index

When the forward bias pulse was applied on one of the Y switch's branch, Fabry-Perot fringes were displayed due to the change in the refractive index. The change in refractive index Δn produces motion of the fringes as if the wavelength is changing by an amount $\Delta'\lambda$. Note that $\Delta'\lambda \neq \Delta\lambda$. For electro-optic effect, $\Delta'\lambda$ can be written as

$$\frac{\Delta V}{\Delta'\lambda} = \frac{dV}{d\lambda} \quad \text{or} \quad \Delta'\lambda = \left(\frac{d\lambda}{dV} \right) \Delta V \quad (5.17)$$

$\Delta'\lambda$ can be calculated directly if the number of fringes during the time of applying the bias voltage signal could be counted on the oscilloscope display. $\Delta'\lambda$ is the number of fringes multiplied by the wavelength separation between any two consecutive maxima, as measured from the Fabry-Perot diagram (0.15nm). That is

$$\Delta'\lambda = \Delta\lambda \times \text{number of fringes} \quad (5.18)$$

The change in refractive index Δn can be calculated from the relation:

$$\Delta n = -\frac{n}{\lambda} \Delta'\lambda \quad (5.19)$$

Using Eqn. (5.17) Δn can be written as

$$\Delta n = -\frac{n}{\lambda} \left(\frac{d\lambda}{dV} \right) V \quad (5.20)$$

where n and λ are the index of refraction of the waveguide before applying the bias voltage and the wavelength in vacuum at which the measurements are taken. $\Delta'\lambda$ is the change in wavelength, which produce the same number of fringes that the applied voltage, V , has produced.

Since the bias current is proportional to the applied voltage in the linear part of the IV characteristics of PIN structure of the waveguide, Eqns. (5. 17) and (5.20) may be written as

$$\Delta'\lambda = \left(\frac{d\lambda}{dI} \right) \Delta I \quad (5.21)$$

and

$$\Delta n = -\frac{n}{\lambda} \left(\frac{d\lambda}{dI} \right) I \quad (5.22)$$

The IV characteristics were discussed in Chapter 3.

5.1.2 Temperature Contribution to the Change in Refractive Index

The change in refractive index of every layer contributes in the estimation of Δn .

For every layer, there are 3 carrier effects to estimate the carrier-induced changes of refractive index: band filling, band-gap shrinkage and free-carrier absorption [33]. For the light propagating with a wavelength of 1550 nm, the photon energy is 0.8 eV. This energy is less than the band-gap energy of InP (1.34 eV) and InGaAsP (1.08 eV). In this case, the band filling and free-carrier absorption contributions are negative while the band-gap shrinkage contribution is positive. By increasing the applied voltage, V , the absolute value of change in refractive index increases due to the increase of carriers. The other contribution to the change in refractive index of each layer is the effect of heating. The temperature rise ΔT in the waveguide is proportional to the dissipated power, P .

$$P = I V = \frac{V^2}{R} = I^2 R \quad (5.23)$$

where I , V and R are the current passing through the waveguide, the applied bias voltage and resistance of the waveguide, respectively.

In case of InP, the refractive index as a function of temperature is given by [36]:

$$n = 3.075 (1 + 2.7e-5 T) \quad (5.24)$$

From Eqns. (5.23) and (5.24), the change in refractive index as a result of the change in temperature is proportional to V^2 or I^2 . This change is positive and become of significant value at high voltages. The above results are valid for TE and TM modes.

The effect of the temperature is the dominating factor if fabrication defects or waveguide damages are present.

5.1.3 Calculation of the Time Constant and Rise Time

Since the waveguide can be considered as a capacitor of capacitance C connected with a resistance R , the bias voltage V will build up across the waveguide as follows

$$V = V_{\max} - V_{\max} \exp\left(-\frac{t}{\tau_{RC}}\right) \quad (5.25)$$

where $V_{\max}$ and t are the maximum voltage and time, respectively. $\tau_{RC} = RC$ is called the time constant. Chapter 3 shows the results for the total capacitance and the total resistance of the straight waveguide. The carrier injection and Δn are proportional to V . Therefore, the change in refractive index Δn can be written as a function of time as follows.

$$\Delta n = \Delta n_{\max} - \Delta n_{\max} \exp\left(-\frac{t}{\tau}\right) \quad (5.26)$$

where $\Delta n_{\max}$ is the maximum change in the refractive index. In Eqn. (5.26), τ may be the electrical time constant ($\tau = \tau_{RC}$) or thermal time constant ($\tau = \tau_T$). The effect of temperature is to produce slower (larger time constant) change in refractive index than expected if the change is dominated by electrical effect.

The rise time is the difference in time between the times at which the waveguide voltage is 10% and 90% of the absolute value of the maximum value.

The rise time is related to the time constant as follows

$$\tau_{\text{rise}} = 2.2 \tau \quad (5.27)$$

5.2 Experimental Setup for Fabry-Perot Measurements

The experimental setup is shown in Fig. 5. 3. A diode laser was adjusted to emit a

(a)

(b)

Fig. 5. 3 The experimental setup for Fabry-Prot measurements

(a) Aligning the input fiber with the waveguide and adjusting the polarization mode.

(b) Obtaining the optical output signal.

beam of wavelength of ~ 1550 nm. The laser light was delivered to the lensed fiber (the input fiber) through a polarizer and a half wave plate. The input lensed fiber was mounted on an XYZ position stage. This lensed fiber was working as a concave lens to focus the laser beam on the facet of the straight waveguide, or the input of the Y junction, mounted on an XYZ position stage. The electrode of the waveguide, or the Y branch, was connected, through a needle probe, to the positive terminal of the pulse generator and the substrate was connected to the ground terminal. As shown in Fig. 5. 3(a), a microscope objective was mounted on another XYZ position stage in front of the output facet, or either Y output branch, to collect the output beam and deliver a wider beam to an infrared (IR) video camera connected to a monitor. The X, Y and/or Z knobs of the position stage of the microscope objective were adjusted so that a clear spot, in case of the straight waveguide, or two clear spots, in case of the Y junction, appeared on the monitor.

A polarizer was placed in the way of the output beam before it reaches the infrared (IR) video camera. The polarizer was adjusted to pass only the TM mode. The half wave plate was rotated until the TM output intensity was at maximum. Then a photo detector was placed between the polarizer and the IR camera. The half wave plate (HWP) was adjusted to get the maximum output power. The output power in this case was in the TM mode.

The microscope objective was replaced by a lensed fiber (the output fiber) to deliver the output power directly to the photo detector as shown in Fig. 5. 3(b). The output fiber was aligned with the output facet of the waveguide until a maximum power was reached.

Both the input and output fibers were polarization maintaining (PM) fibers. The photo detector was connected to one channel of the oscilloscope and the pulse generator output was connected to the other channel. After obtaining and saving the plots for the TM mode

Fig. 5. 4 Output power as a function of time for TE polarization when a potential of 3 V and pulse width of 10 μ s is applied on the straight waveguide of width = 3 μ m.

Fig. 5. 5 Output power as a function of time for TE polarization when a potential of 3 V and pulse width of 5 μ s is applied on the straight waveguide of width = 3 μ m.

at different applied voltages, the half wave plate was rotated 45° and the signal data files were saved for the TE mode at different applied voltages. If a Y junction was tested, the above procedure was repeated for the other branch. The above procedure was repeated for different straight waveguides and Y junctions with different widths either with or without metal electrodes.

5.3 Switching and Rise Time Results for Straight Waveguides with Metal Electrode

The voltage signal was a square wave with pulse repetition rate of 100 Hz and pulse width 5 μs . Low frequency and small duty cycle were used to minimize thermal effects and avoid the waveguide damaging at high voltages. Some devices were tested at 10 μm pulse width and it was found that the switching pulse did not change appreciably after 5 μs as shown in Figs. 5. 4 and 5. 5. Therefore, the 5 μs pulse width was chosen for the applied voltage signals to all the waveguides and it was assumed that the light signal reached its maximum modulation at the end of the 5 μs . The error did not exceed a quarter of a fringe, 0.04 nm in the wavelength scale, for an applied voltage of 8V. This small error was not considered during the calculations.

5.3.1 $\Delta\lambda$ Results for Straight Waveguides

Figs. 5. 6 and 5. 7 show the optical power as a function of time for a straight waveguide of width 3 μm with the TE mode polarization at a square applied voltage signal of pulse width 5 μs and frequency 100 Hz with amplitudes of 5 V and 8 V

Fig. 5. 6 Output power as a function of time for TE polarization when a potential of 5 V and pulse width of 5 μ s is applied on the straight waveguide of width = 3 μ m.

Fig. 5. 7 Output power as a function of time for TE polarization when a potential of 8 V and pulse width of 5 μ s is applied on the straight waveguide of width = 3 μ m.

Fig. 5. 8 Output power as a function of time for TE polarization over a long period of time when a potential of 8 V and pulse width of 5 μs is applied on the straight waveguide of width = 3 μm . A long tail due to thermal relaxation can be seen.

respectively. As shown in these two figures, as the voltage is increased the number of fringes also increases and as a result $\Delta'\lambda$ ($= \Delta\lambda \times \text{number of fringes}$) increase to give higher value of $|\Delta n|$ as shown from Eqn. (5.20).

The figures for the optical power as a function of time for straight waveguides of widths 4 μm and 5 μm , with the TE and TM mode polarization at the same conditions of the 3 μm waveguide, have similar behavior and are not given here. As the waveguide width increases, both the number of fringes, and $\Delta'\lambda$, decrease. This can be attributed to the fact that for small changes in wavelength, the change in wavelength, $\Delta'\lambda$, is proportional to the change in voltage as shown in Eqn. (5. 17).

Fig.5. 8 was taken at the same conditions of Fig. 5. 7 but for longer time scale to show the decay in power due to the heating effect. During the 5 μm voltage pulse, carriers (holes) are injected into the waveguide and the current produces local heating in the waveguide, which decreases the refractive index. The temperature rise slows down with time since the heat is spreading to the surroundings, and the decrease in refractive index becomes slower so that the time to build up a fringe is longer. This can be shown in Fig 5. 8 where fringes become longer with time until the end of the signal pulse width. After the pulse, there are no more carriers and as a result the waveguide begins to cool down. The cooling effect will slow down with time because of the hot surroundings of the waveguide. As a result the fringes spacing again increases with time. In the thermal relaxation part of Fig. 5. 8, both of the number of fringes and $\Delta'\lambda$ are exactly the same as the number of fringes, and $\Delta'\lambda$, in the switching part, during the pulse width time. This is because the cooling in the waveguide is the reverse process of the heating. It can be

Fig. 5. 9 Δn for straight waveguides of widths 3 μm , 4 μm and 5 μm as a function of the current passing through the waveguide circuit for light propagating with TM and TE polarization modes.

noticed that the cooling time, after the pulse width, is longer than the heating time. This can be attributed to the fact that the waveguide is the source of heating. During the pulse, it is always hotter than the surroundings. In case of the cooling, the waveguide will cool fast in the beginning until it has the same temperature as the surroundings and then it will cool down at the same rate of surroundings.

5.3.2 Δn Results for Straight Waveguides

Fig. 5. 9 shows the Δn for straight waveguides of widths 3 μm , 4 μm and 5 μm when light of TM and TE polarization is propagating through them as a function of the current passing through the waveguide circuit. Δn is calculated from Eqn. (5.20). With increasing the voltage, both of $|\Delta n|$ and $\Delta\lambda$, are increasing. For the 3 μm , 4 μm and 5 μm width waveguides, Δn for the TM mode increases linearly with bias current.

In Fig. 5. 9, the Δn values for TE and TM modes are similar. By comparing the Δn for different waveguide widths we found that $|\Delta n|$ increases with decreasing the waveguide width or increasing the current.

5.3.3 Rise Time Results for Straight Waveguides

Table 5.1 shows the average rise time for straight waveguides of widths 3 μm , 4 μm and 5 μm when light of TM and TE polarization is propagating through them. The rise time is in the microsecond range, which is much larger than the expected value. The expected value of the rise time is in the range of nanosecond, as illustrated in Chapter 3.

Table 5.1: The rise time for different straight waveguides

	τ (μs)
3 μm TM	1.7
3 μm TE	2.36
4 μm TM	2.67
4 μm TE	2.4
5 μm TM	2.76
5 μm TE	2.63

This large value of rise time is simply the thermal rise time. This rise time may be called the index modulation rise time because the change in refractive index, as calculated from Eqn. (5.26), is modulated by the dominating thermal effect. As a result, the thermal effect is the dominant effect for the change in refractive index.

The rise time measured for the different Y-junctions of different branching angles, electrode gaps and widths was in the microsecond range, which is much larger than the nanosecond expected range. This can be attributed to the thermal effect, which dominates the nanosecond electrical effect.

A new wafer containing waveguides and Y-switches of the same structure as those in the old wafer was studied using broadband source. The rise time is in the nanosecond range, as we will show later.

5.3.4 Dynamic Fabry-Perot Fringe Calculation

A matlab simulation program was written and run to model the experimental results. Fig. 5.10 shows the simulation results for the 3 μm width waveguide. The program is used to plot the normalized output power and the absolute value of the change in refractive index, $|\Delta n|$, as a function of time based on Eqns. (5.16) and (5.26). In the simulation program, the calculated rise time, τ , shown in Table 5. 1 was used.

By comparing the number of fringes for the measured and calculated output light signal it is found that the number of fringes in case of the calculated signal is approximately the same as those of the measured signal for the 3 μm straight waveguide.

The APSS program is a simulation program to calculate and draw the change of the electromagnetic field of the propagating light into the waveguide with the waveguide

(a)

(b)

Fig. 5. 10: The normalized output power and the absolute value of the change in refractive index, $|\Delta n|$, as a function of time for the straight waveguide of width $3 \mu\text{m}$ and through which light propagates with (a) TM polarization and (b) TE polarization.

dimensions. We discussed the APSS simulation in chapter 4. By running the APSS program for simulation of the straight waveguides of width 3 μm , 4 μm and 5 μm and layer composition and index of refraction shown in Table 4. 1, it was found that the 3 μm waveguide supports only the fundamental mode. For the 4 and 5 μm waveguides, the contribution of the first order mode can no longer be ignored. From the APSS simulation results shown in Fig. 4. 7, it is concluded that the first order mode in the layers around the core may affect the measured results such as the number of fringes and the output power.

5.4 Results Obtained Using Broadband Source and New Sample

To get rid of the Fabry-Perot fringes and the effect of the individual modes, we replaced the Tunics – PR Photonics wavelength tunable laser diode source by a broadband source (Agilent 83438A Erbium ASE source) of wavelength 1550 nm and output power 3.5 mW and Erbium doped fiber amplifier to amplify the light to 30 mW.

To reduce the effect of the equipment response time on the total measured rise time, the Tektronix TDS 3012 oscilloscope (100MHz) and the photo detector set were replaced by the wide bandwidth oscilloscope (Agilent 86100A, 30 GHz). The wires and probes used in connecting the electrodes to the pulse generator were shorter and of better quality to decrease the parasitic capacitance and resistance.

To get rid of the dominating thermal effect, which hides real switching due to the electrical effect, a new sample with the same composition was fabricated.

5.4.1 Straight Waveguide Rise Time

Fig.5. 11 shows the output power from the straight waveguide of 3 μm width as a

Fig. 5. 11 The output power from the straight waveguide of 3 μm width as a function of time when a bias signal is applied (TE mode). The power for TM mode is very low.

function of time when a bias signal is applied (TE mode). The power for TM mode is very low. The rise time was in the range of 10 ns. This value is in agreement with the expected results shown in Chapter 3. This proves that the switching for this new sample is due to the electrical effect.

The power propagating into the straight waveguide was decreasing when the bias voltage, or current, is applied as shown in Fig. 5. 11. The decrease in output power may be due to the carrier induced absorption.

5.4.2 Y-Junction Switching

A Y-junction of branching angle $A=1.57^\circ$, gap between the electrodes $G=0.5\ \mu\text{m}$ and branch width $W=3\ \mu\text{m}$. The rise time was measured using the wide bandwidth oscilloscope (Agilent 86100A, 30 GHz). The rise time was in the range of 7 to 13 ns. This value is in agreement with the expected results shown in Chapter 3. This proves that the switching for this new sample is due to the electrical effect not the thermal.

The power in the active branch was decreasing when the bias voltage, or current, is applied and increasing in the passive branch as shown in Fig. 5. 12. This means that the change in refractive index in the active branch was negative and as a result the input beam is guided into the unbiased branch. This is in agreement with the expected behavior and contrary to the previous results, where switching was dominated by the thermal effect.

The output power of the passive branch for the TE polarization mode is higher than for the TM mode.

To measure the switch's extinction ratio, probe needle is used to contact the

(a) TE mode and active branch

(b) TE mode and passive branch

(c) TM mode and active branch

(d) TM mode and passive branch

Fig. 5. 12 The output power from the Y-junction branch (W3G0.5A1.57) as a function of time when a bias signal is applied.

electrode of one output branch when it is active. The passive branch is either contacted to the probe needle connected to the ground or is not contacted at all. Both cases give the same results. The extinction ratio, ER, can be calculated as follows

$$ER \text{ (dB)} = 10 \log \left(\frac{P_{n_passive}}{P_{n_active}} \right) \quad (5.28)$$

where $P_{n_passive}$ and P_{n_active} are the normalized power for the passive and active branch.

$$P_{n_passive} = \frac{P_{passive}}{P_{o_passive}} \quad \text{and} \quad P_{n_active} = \frac{P_{active}}{P_{o_active}} \quad (5.29)$$

where $P_{passive}$ and P_{active} are the passive and active branch power when potential is applied to the active branch. $P_{o_passive}$ and P_{o_active} are the passive and active branch power when no potential is applied to the active branch. Fig. 5. 13 shows the normalized branch output Power as a function of the applied current. The gap between the power of the passive and active branches at the same current is proportional to the extinction ratio. From Fig. 5. 12 it is shown that the Extinction ratio increases with increasing the current. For the 3 μm Y-junction, of $G = 0.5 \mu\text{m}$ and $A = 1.57^\circ$, the extinction ratio is 14.49 dB for the TE mode and 7.78 dB for the TM mode. The low extinction ratio for the TM mode, compared with the extinction ratio of the TE mode, is due to the low power in the in the active branch as we discussed above.

5.5 Summary and Closing Comments

The rise time was ranged from 1.7 μs to 2.8 μs for straight waveguides and from 0.4 μs to 1.4 μs for the Y-Junction. These values are large due to the thermo-optic switching which is the dominant effect. The thermo optic effect may be due to the defects

Fig. 5. 13 Switching curves of W3G0.5A1.57 Y-branching switch for TE and TM polarization modes.

in the wafer.

To overcome this problem, a new wafer of the same composition as the old wafer was fabricated for further study. A broadband source, a faster oscilloscope, shorter wires, and probes of better quality were used to get more accurate rise time. The obtained rise time is in the range 10 ns for the straight waveguide of 3 μm width and between 7 to 13 ns for the Y switch ($A = 1.57^\circ$, $G = 0.5$ and $W=3 \mu\text{m}$). The switching curves were drawn and the extinction ratio is 14.49 dB for the TE mode and 7.78 dB for the TM mode.

The change in refractive index was in the range of 8×10^{-5} and 1.7×10^{-3} . A matlab simulation program was written and run to estimate the Fabry-Perot fringe pattern produced when the bias voltage applied on the straight waveguide.

6 Conclusions

6.1 Contributions of This Work

The objective of this thesis was to characterize device structures for use in a novel digital optical switch. A group of measurements and simulations were completed to determine the waveguide losses, the effect of metal electrodes, and switching time.

The aim of contact resistance measurements discussed in Chapter 2 was to determine how effective was the implantation region to isolate the metal electrodes, or contact pads. If the isolation implant is successful, the behavior of the TLM after implantation is expected to be like a back-to-back diode. The back-to-back diode structure consists of two P-I-N diodes, one in the forward bias mode, which determines the IV characteristics, and the other in the reverse bias mode, whose reverse bias resistance is the dominating factor for determining the contact resistance.

After implantation, the total resistance became very large, in the range of $100 \text{ k } \Omega$ and the contact resistivity was in the range of the $0.05 \text{ } \Omega\text{-cm}^2$. The TLM pad IV plots showed clear diode-like behavior, confirming the isolation implant was successful.

There were two models available to characterize the sheet resistance and contact resistivity of the DOS electrodes using the TLM. The Marlow and Das model is suitable for comparison between samples before and after implantation, and annealing if applicable while the Reeves and Harrison model gives more accurate values for the contact resistivity. Sample 1 showed bad results after implantation and was not used for further studies of the switch.

Sample 2 showed better results and therefore it was used for fabrication of the switch. Before implantation the total resistance of sample 2 versus the spacing between the contact pads was linear and the total resistance was less than 350 Ω . The contact resistivity was in the range of $\sim 10^{-5} \Omega\text{-cm}^2$.

The IV characteristics of the straight waveguide were studied in Chapter 3. The resistance, maximum current, maximum voltage, and the turn-on voltage of the PIN diode under a straight waveguide section were calculated. The resistance, maximum voltage and turn-on voltage each decreases while the maximum current increases as the waveguide width is increased.

The capacitance of the system was due to the junction capacitance and the parasitic capacitance in parallel. The parasitic capacitance is much larger than the junction capacitance. The total capacitance is about 3.4 pF.

The measured switch rise time is ~ 10 ns while the calculated rise time due to the RC coupling is about 39.3 ps for the different waveguides under study.

The waveguide loss using the Fabry-Perot technique was calculated in Chapter 4. A straight section of waveguide with two cleaved ends was modeled as a Fabry-Perot cavity. From the fringe pattern in the transmitted optical signal, the waveguide loss was calculated. For the TM mode the loss was 15 dB/cm to 18 dB/cm without metal electrode present, and 18.4 dB/cm to 24.5 dB/cm with metal electrode present. For the TE mode the loss was from 4 dB/cm to 11.5 dB/cm without metal electrode present, and 6 dB/cm to 7.5 dB / cm with metal electrode present.

Only the fundamental (00) mode can propagate in the 3 μm wide waveguide. However, in the 4 μm wide and 5 μm wide waveguides, the first-order (10) mode can

also propagate. This mode has a maximum lobe in the substrate below the ridge. When coupling to fiber for experimental measurement, one must be sure to couple to the (00) mode.

The rise time and change in refractive index were calculated in Chapter 5. The rise time was ranged from 1.7 μs to 2.8 μs for straight waveguides and from 0.4 μs to 1.4 μs for the Y-Junction. These values are large due to the thermo-optic switching which was the dominant effect. The thermo-optic effect may be due to the defects in the wafer.

To overcome this problem, a new wafer of the same composition as the old wafer was fabricated for further study. A broadband source, a faster oscilloscope, shorter wires, and probes of better quality were used to get more accurate rise time. The obtained rise time is in the range 10 ns for the straight waveguide of 3 μm width and between 7 to 13 ns for the Y switch ($A = 1.57^\circ$, $G = 0.5$ and $W = 3 \mu\text{m}$). The switching curves were drawn and the extinction ratio is 14.49 dB for the TE mode and 7.78 dB for the TM mode.

The change in refractive index was in the range of 8×10^{-5} and 1.7×10^{-3} . A matlab simulation program was written and run to estimate the Fabry-Perot fringe pattern produced when the bias voltage applied on the straight waveguide.

6.2 Recommendations

TLM measurements showed that O^+ implant is effective in isolating the metal electrodes.

The use of a broadband source as a light source or use of antireflection, AR, coatings of the end facets of the waveguide are recommended to get rid of the produced Fabry-Perot fringes during the application of the forward bias voltage.

The material quality has to be examined to find the reasons that one sample had strong thermal effect.

More simulations need to be done to achieve a waveguide that support the fundamental mode only. Also ultra fast equipment, with response time in the range of picoseconds, should be used to measure and obtain the switching curves and switching time.

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